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The Development of a Methodology to Compile an Insulator Pollution Severity Application Map for South Africa

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Thesis submitted for the Masters Degree in Engineering (electrical) at the University of Stellenbosch

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DECLARATION:

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and has not been previously, in its entirety, submitted at any university for a degree. The sources are acknowledged in the references.

Donovan Pietersen

SYNOPSIS

The main objective of this research project was to develop a methodology which can be used to assist in developing an insulator pollution severity application map (INSMAP), more particularly for South Africa. The techniques must be able to assist in determining pollution severity levels.

At the inception of this project a phase one insulator pollution severity application map was available; this map was based on an existing corrosion map, climatic maps and dust gauge measurements. The phase one map was conservative and did not highlight localised pollution. To confirm and possibly improve on this map, a phase two map was developed, which was based on feedback from Eskom field personnel via an electronic insulator pollution questionnaire survey (based on IEC 60815 guidelines). The questionnaire was incorrectly completed in most cases due to a lack of understanding by field personnel of environmental pollution and the impact on insulator performance. This resulted in an unrealistic map with exaggerated contamination levels.

To confirm the findings of the phase one map, a phase three approach was followed, which was focused on an investigation into pollution measurement techniques and methodologies. Based on the phase one map, a need was identified to confirm by measurements the impact of distance-to-coast. Also, the validity of installing a dust gauge at 3 metres above ground level, while insulators are at a height of 8 to 40 meters, had to be investigated. Two pollution monitoring programmes were established: a distance-to-coast and height-above-ground environmental pollution study. Various test methods are described with a complete testing procedure, descriptive equations and related pollution severity classifications for insulator pollution (DDG and ESDD) and corrosion (CLIMAT and metal specimens).

The distance-to-coast test results confirm the phase one map, while the height-above-ground measurements justify the installation of dust gauges at 3 metres above ground level.

Good correlations were found for the distance-to-coast study between insulator pollution severity and corrosion rates.

From the height-above-ground study, a slight (insignificant) decrease in pollution levels was found for increase in height for insulator pollution and corrosion tests.

Recommendations are made on setting up a basic pollution monitoring station.

Key words: Insulator pollution, Corrosion, Distance, Height.

SAMEVATTING

Die hoofoogmerk van hierdie navorsingprojek was die ontwikkeling van 'n metodiek om 'n isolator besoedelingskaart saam te stel, meer spesifiek vir Suid Afrika. Die tegnieke moet die besoedelingsvlakke en impak-afstand van elke besoedelingvlak aandui.

'n Fase een isolator besoedelingskaart het reeds bestaan by die aanvang van hierdie projek, hierdie kaart was gebaseer op 'n bestaande korrosiekaart. Die fase een kaart was baie konserwatief en het nie lokale besoedeling aangedui nie. Dit was besluit om die fase een kaart te verbeter en 'n fase twee kaart was ontwikkel wat gebaseer was op 'n elektroniese isolator-besoedeling vraelys wat deur Eskom se tegniese veldpersoneel voltooi is. Die vraelys is in baie gevalle verkeerdelik ingevul, as gevolg van 'n gebrek aan die kennis oor besoedeling en die impak daarvan op isolatorprestasie. Dit het tot 'n onrealistise kaart gelei met onakurate besoedelingsvlakke.

'n Fase drie ontwikkeling is begin, waar 'n ondersoek gekyk het na metingstegnieke en metodiek vir besoedelingsmetings. 'n Volledige toetsprosedure, beskrywende vergelykings en besoedelingklassifikasies is ontwikkel vir die isolator-besoedeling (DDG en ESDD) en korrosietoetse (CLIMAT en metaal monsters). Toetsstasie seleksiekriterea vir die geografiese plasing van 'n toetsstasie is vasgestel. Twee toetsprogamme is vasgestel: 'n afstand-van-see en 'n hoogte-bo-grondvlak besoedelingsstudie.

Die afstand-van-see studie het 'n impak-afstand vir elke besoedelingsvlak vir beide isolatorbesoedeling en korrosietoetse vasgestel. 'n Goeie korrelasie is vasgestel tussen isolator-besoedeling en korrosievlakke.

Vir die hoogte-bo-grondvlak studie was gevind dat daar 'n klein (weglaatbare) vermindering in besoedelingsvlakke met toename in hoogte bo grondvlak vir isolator-besoedeling- en korrosievlakke onstaan. 'n Goeie korrelasie bestaan tussen isolator-besoedeling- en korrosievlakke.

Aanbevelings word gemaak vir die opstel van 'n basiese besoedelingsmetingstasie.

Sleutelwoorde: Isolator besoedeling, Korrosie, Afstand, Hoogte.

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LIST OF ABBREVIATIONS

ACM	Atmospheric Corrosion Measurements
AVG	Average
ASTM	American Standard for Testing of Metals
CSIR	Council for Scientific and Industrial Research
CLIMAT	CLassify Industrial and Marine ATmosphere
DDG	Directional dust deposit gauge
DIPSAM	Dynamic insulator pollution severity application map for S.A.
ERI	Energy Research Institute
ESCOM, Eskom	Electricity Supply Commission, later changed to Eskom
ESDD	Equivalent salt deposit density
FSA	Field Service Area
IEC	International Electrotechnical Commission
IPSAM	Insulator pollution severity application map for S.A.
ISO	International for Standardisation
KIPTS	Koeberg Insulator Pollution Test Site
NSDD	Non-soluble deposit density
TSA	Technical Service Area
TSC	Technical Service Centre

INTRODUCTION

The deposition of salts and dust, due to marine or industrial environments, on the surface of insulators adversely affect the performance of power lines or substations. The effect is aggravated by the wetting of the pollutants, normally by rain or fog, and a conductive electrolyte is formed. This allows the flow of leakage currents on the surface of the insulator, and, if not brought under control, will increase and finally develop into a flashover. The insulator, the backbone of the network, must therefore be able to cope with the most extreme environment it is to encounter.

Outdoor electrical distribution and transmission networks pass through an array of environments that differ from light to very heavy pollution severity. These pollution environments coupled with local climatic conditions can adversely affect the performance of insulators leading to premature ageing of insulators and, in the worst case, to insulator pollution flashovers.

One of the main challenges facing the electrical power industry is to limit the unwanted loss or disruption of supply, causing loss of revenue, inconvenience and often fatality. Various research programs undertaken over many years empirically proved that insulator pollution flashovers on high voltage transmission lines contribute a large proportion to power disruption [11], [12]. Insulator flashovers occur due to various reasons; some of the major causes are given as lightning, over-voltages due to switching, and most importantly - insulator pollution.

Various international organisations identified the problems and risks associated with insulator pollution and, therefore, task groups were established to investigate solutions to mitigate the effects. One such organisation is the International Electrotechnical

Commission (IEC). IEC published a guideline for the selection of outdoor insulators in respect of polluted conditions, the IEC 60815 guideline [3]. Another organisation, CIGRÉ, also published a document, by the CIGRÉ Taskforce 33-13-01 [2], to provide engineers with the tools to select and dimension outdoor insulators most suited to a given environment.

The abovementioned guidelines have been developed to assist the engineer in the optimal selection of insulators for a particular environment; a key criterion is the fact that the pollution severity of the site be known. The latter is in most cases not well defined or not known at all, and too often, the end result is the wrong type of insulator for a particular environment.

Eskom and the other electricity utilities throughout South Africa use a large number of insulators on their transmission and distribution networks and in substations. Eskom recognised the shortcomings associated with insulator selection and initiated a research project to "Develop a high-level insulator pollution application map for South Africa". The objective is to develop a tool that would assist design and maintenance engineers in the identification of insulator pollution severity levels and to assign a minimum specific creepage distance in respect of the pollution severity [62], [63].

As part of this research project, the author was tasked to investigate the methodology to compile an insulator pollution map.

1.1 BACKGROUND

The need has arisen for an in-depth study of atmospheric pollution levels prevalent throughout South Africa. Accurate information on the type of pollution and its severity will enable designers and maintenance personnel to choose insulators suited to a particular environment. One way of achieving this goal is to develop an insulator application map capable of indicating severity levels, at the same time, prescribing a corresponding minimum specific creepage distance for each pollution severity encountered.

At the inception of this project a phase one insulator pollution severity application map was available, which was based on a corrosion map, climatic maps, and dust gauge

measurements. The map consisted of all the Eskom technical service areas (TSAs) throughout South Africa with each TSA classified in terms of the highest pollution severity in that area. This approach was conservative and did not highlight localised pollution.

1.2 OVERVIEW

To confirm and possibly improve on the phase one map, the phase two map was developed. This map was based on an electronic insulator pollution questionnaire that was completed for each of the Eskom technical service areas (TSAs) throughout South Africa. The questionniare was based on the IEC 60815 guidelines [3]. The phase two map was found to be unrealistic and with gross exaggeration of the contamination levels for most of the TSAs when compared to results for the phase one map.

As a further development to confirm the findings of the phase one map, a phase three approach was followed, which was focused on an investigation into pollution measurement techniques and methodologies. Two environmental pollution monitoring programmes were established: a distance-to-coast study (to confirm the phase one map) and height-above-ground study (to confirm the dust gauge installation at 3 metres). Practical guidelines and test protocols are described for dust deposit gauges (DDG), equivalent salt deposit density (ESDD), and corrosion measurements – enabling the reader to execute any test. Measurements of insulator pollution severity levels and corrosion rates in relation to distance-to-coast and height-above-ground were carried out and the results are reported.

1.3 RESEARCH OBJECTIVE AND SCOPE OF WORK

The main objective of this research project was to develop a methodology which can be used to compile a pollution severity map, more particularly an insulator pollution severity application map (INSMAP) for South Africa. The methodology must be able to identify pollution severity levels and an area of impact for each pollution severity level; taking into account factors such as atmospheric pollution, climate, and topography.
In this project a wide range of pollution monitoring was covered which can be best categorised into the following:

- Establishing test site selection criteria,
- Setting up a distance-from-coast pollution monitoring site,

- Setting up a height-above-ground pollution monitoring site,
- Analysing measurement results for each monitoring study (distance and height) to determine the influence on pollution severity levels,
- Comparing insulator pollution measurements with corrosion test results.

1.4 STRUCTURE OF THESIS

The thesis comprises eight chapters.

In **Chapter 1** the background, project overview and research objective and scope is stated.

In **Chapter 2** the mechanisms comprising insulator flashovers and corrosion are discussed. The effect of climatic conditions and pollutants are also covered.

In **Chapter 3** the test procedure, descriptive equations and related pollution severity indices for insulator pollution and corrosion are given.

In **Chapter 4** the preliminary versions of the insulator pollution severity application map (IPSAM) is discussed. The phase one map based on a literature review and, the phase two map the outcome of an insulator pollution survey.

In **Chapter 5** the criteria to select a test site is covered. This chapter also includes the method that was followed to set up a test site for distance-to-coast pollution measurements along the Koeberg-Muldersvlei 400kV line. The environmental and climatic conditions are discussed.

In **Chapter 6** the test results for the distance-to-coast study are provided and discussed.

In **Chapter 7** test results from the height-above-ground study are discussed.

Chapter 8 contains a summary of the findings, conclusions and recommendations.

These chapters are followed by a list of references and Appendices.

2

THE MECHANISMS OF INSULATOR POLLUTION AND CORROSION

This chapter gives a review of the mechanisms causing insulator pollution and flashover. Metal corrosion depends on the presence of moisture and ionic salts, the same factors causing insulator pollution flashovers. It was therefore decided to investigate the mechanisms causing corrosion and to correlate the findings with insulator pollution.

It is worth noting that this study is only limited to atmospheric pollution and its influence on insulator pollution and corrosion.

Pollution sources

Any source that emits a substance into the atmosphere can be classified as a pollution source. The effect of these emissions on an area defines the pollution nature of that environment. The three pollution environments most commonly found and render the biggest problems are marine environments, industrial environments and, desert environments [13].

Electrolyte

A current flows through a liquid only if ions are present in it. Electrical conductive fluids are known as electrolytes [40]. An electrolyte can be described as a liquid (or solution) containing ions, which are particles bearing electrical charge [39].

In will be shown later in this chapter that an electrolyte must be present in both the insulator pollution and the corrosion process for the reaction to excel (see section 2.3).

2.1 INSULATOR POLLUTION

In the high voltage field, the insulator (a nonconductive mechanically strong device) is used to support and house high voltage components, and insulate them from earth potential. Distribution and transmission lines pass through an array of environments that may differ from a light to very heavy pollution severity. High voltage insulators become polluted when exposed to the environment. When critically polluted and wetted the insulators could flash over, resulting in unwanted outages.

2.1.1 Pollution Types

Pollution is classified into two main categories, namely active pollution that forms a conductive layer, and inert pollution that influences the conductive layer. These categories and typical examples are given below [11]:

- **Active Pollution:** forms a conductive layer.
  - Conductive pollution : metallic dust.
  - High solubility salts : (NaCl, $MgCl_2$, $NaSO_4$, etc.
  - Low solubility salts : Gypsum, fly ash, cement
- **Inert pollution:** influences conductive layer.
  - Hydrophillic pollution: Kaolin. cement, clay, SiO_2, etc.
  - Hydrophobic pollution: Silicone rease, oil, etc.

Active pollution is subdivided into conductive pollution (which is permanently conductive), high solubility salts (that is, salts that dissolves readily into water), and low solubility salts (need a large volume of water to dissolve).

Inert pollution is classified as either hydrophilic (when it absorbs water – increase the wetting properties of the layer and forms a continuous conducting film) or hydrophobic (when it repels water – cause the water to form droplets).

2.1.2 Insulator pollution flashover process

Insulator pollution problems existed since the early attempts to transport (conduct) electricity outdoors. Many years later, problems as a result of electrical insulation breakdown still exist due to pollution (severity) and wetting. A constant effort is made to improve the understanding of the processes leading to insulator pollution problems and how to mitigate them. Researchers such as Wilkens [46], Hampton [47], and Alston [48] used mathematical models to predict the flashover voltage and critical current that leads to flashover. The model consisted of [13]:

- a basic insulator, and
- a partial arc in series with the resistance of an unbridged section of the pollution layer.

The development of the pollution flashover is discussed below and is divided into six phases. In nature these phases or sequence are not distinct but rather occur as a seamless unity, as explained below [77]:

- **Phase 1:** The insulator surface becomes coated with a layer of pollution (salts, acids, or alcalines). Studies have shown that the most important mechanism of pollutant deposit is through the movement of air. If the pollution is deposited as a layer of liquid electrolyte (i.e. salt spray), phases 3 to 6 may happen immediately. If the pollution is nonconductive (high resistance) when dry, some wetting process (phase 2) is necessary for leakage current activity and flashover to occur.

- **Phase 2:** A conductive layer (i.e. an electrolyte) is formed on the insulator surface (the surface is wetted either completely or partially); this normally caused by fog, mist, light rain, melting snow or ice. Heavy rain is a complicating factor: it may either wash away the electrolytic components or part or the entire pollution layer without initiating other phases in the breakdown process, or it may promote flashover by bridging the gaps between sheds.

- **Phase 3:** Once an energised insulator is covered with an electrolyte, surface leakage currents flow. The energy (heating effect) causes part of the contamination layer to dry out.

- **Phase 4:** The heating effect is not uniform, and in places the conducting path becomes broken by dry bands which interrupt the flow of leakage current.

- **Phase 5:** The line-to-earth voltage applied across the dry bands (which may only be a few centimetres wide) causes air breakdown and the dry bands are bridged by arcs which are electrically in series with the resistance of the undried portion of the pollution layer. This causes a surge of leakage current (energy) each time the dry bands on an insulator surface spark over, see figure 2.1.

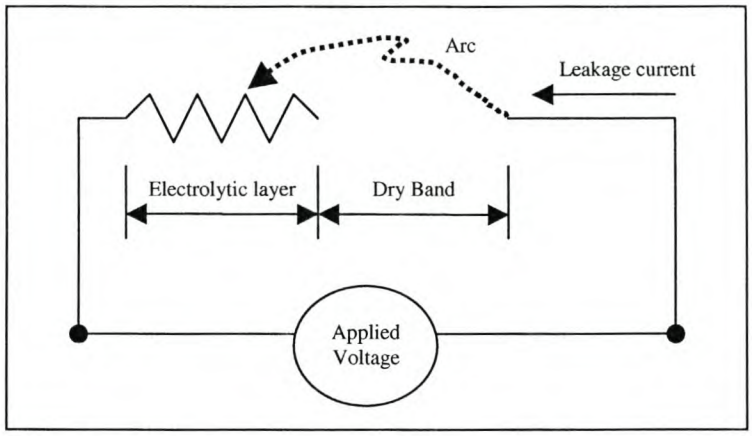

Fig. 2.1 Electrical model of a dry band arc

- **Phase 6:** If the resistance of the electrolyte is low enough (conductivity high), the arcs bridging the dry bands are sustained and are elongated along the insulator, bridging more and more of its surface. This in turn reduces the resistance in series with the arc and allows an increase in current (more energy) permitting even more of the insulator surface to be bridged. If the arc reaches a critical length it completely cross the rest of the gap and a line-to-earth fault (flashover) is established.

The whole process can be summarised as an interaction between the insulator surface, pollutants, wetting conditions, and applied voltage.

2.1.3 Effect of leakage current

It has been estimated that the power-frequency flashover voltage of an insulator can be reduced by a factor of as much as eight when moderately polluted. It is therefore important to monitor the presence of a conducting electrolytic pollution layer on an insulator surface. Leakage current is recognised worldwide as one of the main parameters for performance measurement of insulators. Small currents (in the order of several mA) can cause severe damage to non-ceramic insulating materials (due to sparking). This current degrades the insulation and finally lead to electrical and/or mechanical breakdown of the insulator [21].

It has also been shown that the flashover probability becomes very high if the insulator leakage current approaches a certain threshold value. This value has been defined, based on experimental work by Verma [73], as the peak leakage current one cycle before flashover (I_{max}):

$$I_{\max} = \left(\frac{S_{CD}}{15.32} \right)^2 \tag{2.1}$$

with S_{CD} the specific creepage distance, given by

$$S_{CD} = \frac{L}{U_{\max}} \tag{2.2}$$

where L : total insulator creepage distance in mm

U_{max} : maximum rms system voltage phase to phase in kV

Thus the measured values of the peak leakage current over the insulator can be compared to the calculated I_{max} value and the risk of potential flashover determined. Holtzhausen [78] proposed a permissible value of the peak leakage current (I_{perm}) as:

$$I_{perm} = 0.25 \cdot I_{\max} \tag{2.3}$$

where I_{perm} : highest permissible peak value of the leakage current in ampere

The surface layer resistance is the main factor determining the magnitude of the insulator leakage current and also whether an insulator will flash over or not [21].

2.1.4 Mechanism of pollution deposit on insulators

Pollution is deposited through various mechanisms on an insulator surface, such as:

- due to electrostatic attraction of electrically charged particles, or
- by gravity, or
- as a result of the aerodynamic catch of the insulator.

Of the abovementioned mechanisms, the aerodynamic catch is by far the most important. Figure 2.2 illustrates the mechanism of aerodynamic catch.

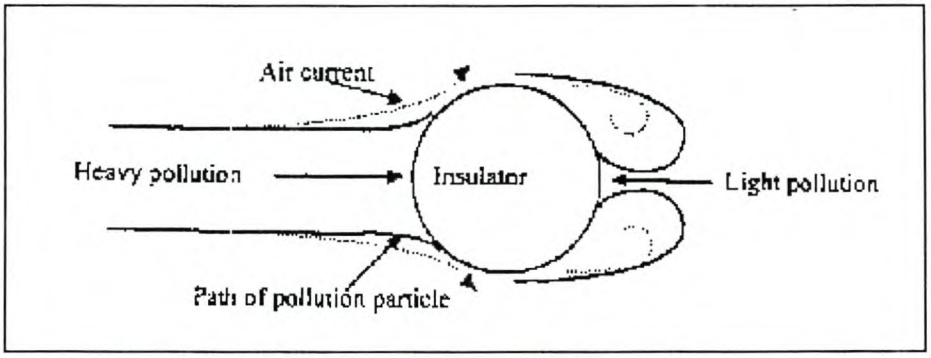

Fig. 2.2 Pollution deposit by aerodynamic action

When air containing suspended particles flows around an insulator, the particles is not deflected around the insulator to the same extent – their densities play a role. Dense particles such as sand will not deflect at all and will be deposited on the leading side of the insulator. Particles with densities similar to air will follow the air currents more closely and will be deposited on the lagging side of the insulator where vortices are present and the curvature of the air flow is sharp [77].

2.1.5 Effect of climatic conditions on insulator pollution severity

Wetting of the insulator surface can take place in various ways. Typical examples are discussed below.

Fog, mist and light rain

Impingement of pollution by water droplets occurs in fog, mist or light rain. This mechanism, depending on wind, can wet the under surface of the insulator more effectively than the condensation mechanism.

Fog can occur when the air flows over a cool surface. The radiative cooling mechanism for condensation depends directly on radiation exchanges at the surface. When net radiation is negative, particularly on a calm, clear night, the air will be cooled below its dew point and ground fog will result. This will begin to form, very close to the ground, an hour or two after midnight and will gradually thicken and deepen as the night progresses.

Another cooling mechanism producing fog is associated with horizontal movement of air. If a warm air stream starts top blow over a cooler surface, the air itself rapidly adjusts to the temperature of the new surface, Again, given sufficient cooling, or sufficient moist air, fog will result.

Condensation or dew

Condensation occurs when the surface temperature of the insulator falls below the dew point temperature.

On a clear still night, the insulator surface, particularly the top surface, loses heat through radiation to the night sky faster than heat can be supplied to it by air currents. If the temperature drops below dew point, moisture forms on the surface of the insulator. These conditions are particularly prevalent in desert environments at night.

Dew condensation wetting is a major cause of flashover on insulators. Studies have shown that this often occurs in the early morning hours.

Moisture absorption

The wetting of the pollution layer on an insulator can occur through moisture absorption by insoluble components of the pollution layer.

If the vapour pressure in the atmosphere is higher than that of the solution vapour pressure, the solution absorbs moisture. The vapour pressure of aqueous solutions is always higher than water vapour pressure. The rate of moisture absorption on the insulator surface depends upon the chemical composition of the pollution. The effect of intense and continuous moisture absorption can cause long-lasting surface discharges at operating voltages or can be the reason for flashover a short time after the line has been energised.

Natural cleaning of the insulator will take place under rain conditions. The pollution dissolves into the water and the run off removes it from the surface.

Critical wetting

It has been shown that the conductivity of the pollution surface layer is the crucial factor that determines the likelihood of flashover. The worst or critical condition (critical wetting) therefore occurs when the environmental influence results in the highest surface conductivity.

A wetting rate is *critical* when it is fast enough to wet the pollution sufficiently for the flashover to take place and slow enough not to wash the pollutants from the insulator surface. In summary, under critical wetting conditions a pollution flashover is most likely to occur.

In a specific environment, knowledge of the pollution type can assist in determining the critical wetting conditions. The critical wetting for the various pollution types are given below (see section 2.1.1 for examples of pollution types) [21].

- **Active pollution**:
  - **Conductive pollution**, wetting always critical.
  - **High solubility salts**, wetting critical under a **low wetting rate** such as mist, dew, or light rain.
  - **Low solubility salts**, wetting critical under **high wetting rate** such as heavy rain.

- **Inert pollution**:
  - **Hydrophilic** pollution, **enhances** pollution wetting.
  - **Hydrophobic** pollution, **inhibits** pollution wetting.

Note: Knowledge of the wetting conditions which resulted in pollution flashovers in a specific area in the past, will assist in defining the critical wetting for that area.

2.2 ATMOSPHERIC CORROSION

Atmospheric corrosion is one of the most widespread forms of corrosion on electric networks because more than 80% of the installations are in the open. The losses produced by corrosion, calculated in terms of cost of the destroyed material, are only a small part of the real damage. In addition to the cost of material, great amounts are spent on repairing the defects produced by corrosion, replacing destroyed instrumentation, over-sizing the installations to prevent failures, and expensive protective coatings [22].

Atmospheric pollution is measurably accelerating corrosion caused by natural elements of the environment. A study of the particular features of air pollution is required, and there is a need to determine the environmental aggressiveness towards metal [22].

2.2.1 Mechanism of Corrosion

Corrosion can take place in the atmosphere, underwater, or underground. It should be mentioned that *this study is limited to atmospheric corrosion.*

Stern *et al* [14] stated that metals corrode either because of the direct action of an acidic and alkaline compound:

$$H_2SO_4 + Zn \rightarrow ZnSO_4 + H_2 \quad (2.4)$$

$$2\,NaOH + 2\,H_2O + Zn \rightarrow Na_2Zn\,(HO)_4 + H_2 \quad (2.5)$$

or as a result of a formed electrolytic cell with the pollutant as an electrolyte

$$\text{Anode:} \quad Zn \rightarrow Zn^{2+} + 2e \quad (2.6)$$

$$\text{Cathode:} \quad 2\,H^+ + 2e \rightarrow H_2 \quad (2.7)$$

In the formed cell, the metal goes into solution at the anode and hydrogen is liberated at the cathode.

Corrosion process

Cited from Schweitzer *et al.* [39], the corrosion process in metals is caused by the flow of electricity from:

- one metal to another or a recipient of some kind, or
- from one part of the surface of one piece of metal to another part of the same metal when conditions permit the flow of electricity.

Furthermore, a moist conductor or electrolyte must be present for this flow of energy to take place. The presence of an electrolyte is a key condition for the process of corrosion to occur. Water, therefore, especially salt water, is an excellent electrolyte.

Simply stated, energy (electricity) passes from a negative area to a positive area through the electrolyte medium. Thus, to have corrosion take place in metals, one must observe:

1) an electrolyte,
2) an area or region on a metallic surface with a negative charge in relation to the second area, and
3) the second area with a positive charge in opposition to the first.

Sometimes the situation becomes further involved. The flow of energy (electricity) may be from one metal to another or from one metal recipient of some kind, which might be the soil. This is due to various environments within a given soil. Soils frequently have contained dispersed metallic particles or bacterial pockets that provide a natural electrical pathway with buried metal. If an electrolyte is present and the soil is negative relative to the metal, the electrical path will occur from the metal to the soil, and corrosion results.

2.2.2 Types of corrosion

Various types of corrosion occur. Typical atmospheric corrosion types are provided below:

- uniform
- electrochemical
- galvanic
- concentration cell
- erosion corrosion

2.2.2.1 Electrochemical corrosion

The cell in figure 2.3 illustrates the corrosion process in its simplest form. The cell includes the following essential components:

1) A metal anode
2) A metal cathode
3) A metallic conductor between the anode and cathode
4) An electrolyte (conductive fluid) in contact with the anode and cathode but not necessarily of the same composition at the two locations.

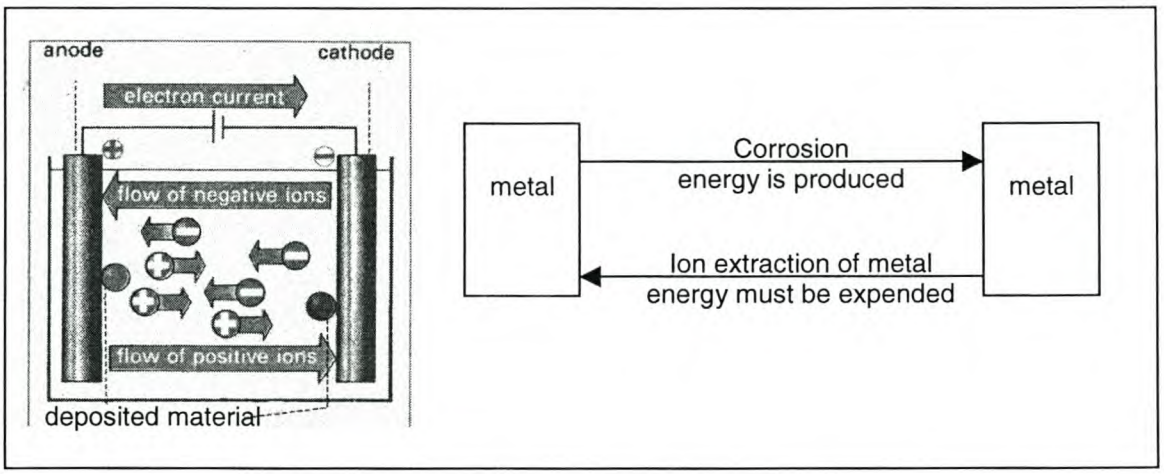

Fig. 2.3 Simple cell showing components necessary for corrosion [40]

In addition, oxygen will usually be present as a depolarising agent. As shown, these components are arranged to form a closed electrical path or circuit. In the simplest case, the anode would be one metal, perhaps iron, the cathode another, say copper, and the electrolyte might, or might not, have the same composition at both electrodes. Alternatively, the electrolyte could be of the same metal if the electrolyte composition varied.

If the cell, as shown, were constructed and allowed to function, the following would occur:

- An *electrical current would flow* through the metallic conductor and the electrolyte.
- The anode would corrode (rust, if the anode were iron); chemically, this is an oxidation reaction (loss of electrons due to chemical reaction).
- Simultaneously, a non-destructive chemical reaction (reduction – gain of electrons by a constituent of a chemical reaction) would proceed at the cathode, usually producing

hydrogen gas on the cathode. When the gas layer insulates the cathode from the electrolyte, current flow will stop, thus, polarising the cell. However, oxygen or some other depolarising agent is usually present to react with the hydrogen, reducing this effect; hence, the cell would continue to function.

If the conductor were replaced with a voltmeter, a difference of potential could be measured between the electrodes. The difference in potential that causes these electric currents is mainly due to contact between *dissimilar metallic conductors* or differences in concentration of the solution, generally related to dissolved oxygen in natural waters.

The metal undergoing electrochemical corrosion need not be immersed in a solution, but it may be in contact with moist soil, or patches of the metal surface may be moist [39]. For the latter, currents will flow over the surface of the metal between the polarised points causing localised corrosion. For metals exposed to the atmosphere this process normally occurs uniformly.

2.2.2.2 Galvanic corrosion

Galvanic corrosion (corrosion by cell formation), or *dissimilar metal corrosion* as it is better known, is a form of degeneration that occurs in the most unusual places and often cause the most painful professional headaches [39].

Points between two types of metals are particularly susceptible to corrosion if moisture condenses at the interface; this is because of the galvanic currents that will flow between these metals. When moisture penetrates between two different metals, this leads to the formation of a cell. The baser of the two metals (the one which is higher in the electromotive series) gradually dissolves (corrode) [40].

As an example we will take an angle iron to which a copper plate has been bolted (as shown in figure 2.4). If moisture has penetrated into the space between the two metals, it acts like an electrolyte so that; in this case, an electrochemical cell with a voltage of 0.78V is formed. The poles of this voltage source are, however, not insulated from each other but connected at various points of contact between the metals thus, there is a continuous flow of current. The flow of current in this case means iron ions are

continuously entering the electrolyte and the iron electrode is therefore worn away (migration of metal ions). Corrosion spreads through the iron, as shown by the following equation.

$$Fe \rightarrow Fe^{2+} + 2 \text{ electrons} \qquad (2.8)$$

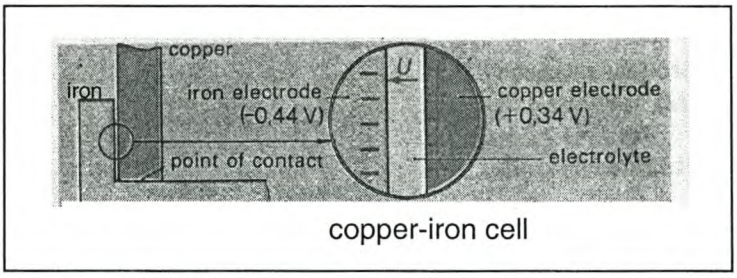

Fig. 2.4 Process of corrosion by cell formation (galvanic corrosion)

Table 2.1 gives a restricted list of metals, which are used in electrical contacts in one form or another. The aluminium end of the series is known as the "active" end and the gold end of the series as the "passive'' end.

Table 2.1: Galvanic series as given by SABS 0199-1985 [16]

	Metal	Standard electrode potential at 25 °C
1.	Aluminium	-1.67 Corroded end (anodic)
2.	Zinc	-0.76
3.	Mild steel	-0.44
4.	Cadmium	-0.40
5.	Stainless Steel (active)	-0.30
6.	Nickel	-0.25
7.	Tin	-0.14
8.	Lead	-0.13
9.	Copper	+0.34
10.	Stainless steel (passive)	+0.50
11.	Silver	+0.80
12.	Carbon	+0.81
13.	Mercury	+0.85
14.	Platinum	+1.20
15.	Gold	+1.7 Protected end (cathodic)

The less noble of two metals will become the anode and will corrode. For instance, in a cell using zinc and copper, negative ions will migrate from the copper (cathode) towards the zinc (anode), and the latter will corrode [16].

2.2.2.3 Atmospheric corrosion

Atmospheric corrosion differs from the action that occurs in water or underground, in that a plentiful supply of oxygen is always present. Here, the formation of insoluble films and the presence of moisture and deposits from the atmosphere become the controlling factors; an additional factor that affects the corrosion rate is the presence of contaminants such as sulphur compounds and the salt particles. Nevertheless, atmospheric corrosion is mainly electrochemical, rather than a direct result of chemical attack by the elements. The anodic and cathodic areas, however, are usually quite small and close together, so that, generally, corrosion is apparently uniform, rather than in the form of severe pitting as in water or in soil [39].

Atmospheric corrosion is a complicated electrochemical process taking place in corrosion cells consisting of base metal, metallic corrosion products, surface electrolyte, and the atmosphere. Because this is an electrochemical process, an electrolyte must be present on the metal for corrosion to occur. In the absence of moisture, which is the most common electrolyte associated with atmospheric corrosion, metals corrode at a negligible rate. For example, carbon steel parts left in the desert remain bright and tarnish free over long periods. Also, in climates where the air temperature is below the freezing point of water or of aqueous condensation on the metal surface, rusting is negligible because ice is a poor conductor and does not function effectively as an electrolyte.

Atmospheric corrosion depends on:

1) the moisture content present,
2) the corrodant (dust and the presence of other impurities in the air), and
3) chemical or electrochemical properties present.

All of which have an effect on the condensation of moisture on the metal surface and the resulting corrosiveness. Air temperature can also be a factor.

2.2.5 Specific atmospheric corrodants

The primary contaminants in the air that lead to atmospheric corrosion are [39]:

- SO_x (oxides from sulphur)
- NO_x (oxides from nitrogen)
- Chlorides
- Oxygen

These contaminants are found in industrial and urban areas. In addition to these general contaminants, other pollutants may be present in local areas.

SO_x

Sulphur dioxide (SO_2) is the primary (and most common pollutant) corrosive element found in industrial atmospheres. It is formed as a result of the burning of fossil fuels, such as coal and oil, and of the combustion products from the incineration of organic and hazardous wastes. The sulphur dioxide is oxidised by water droplets to form sulphuric acid, which is highly corrosive in dilute concentrations [39].

Atmospheric corrosion resulting from sulphur pollutants is usually confined to areas having a high population, many structures, and severe pollution.

Deposition of sulphur compound is accompanied by:

1. Dry deposition
   a) Absorption of sulphur dioxide gas on metal surfaces.
   b) Impaction of particles (sulfates).
2. Wet deposition
   a) Removal of gas from the atmosphere by precipitation in the form of rain or fog.

The dry deposition of sulphur dioxide is the primary deposition process responsible for the atmospheric corrosion of metallic structures.

NO_x

NO_x emissions are also the result of a combustion process but of a different source than those producing SO_x emissions. Energy production and road traffic are the main sources of NO_x.

During the combustion process, the nitrogen oxides are emitted as NO, which is oxidised to NO_2, which can be further oxidised to HNO_3. This latter reaction has a very slow rate; therefore, in the immediate vicinity of the emissions, the predominant contaminant is NO_2. At further distances the concentrations of nitric acid increases.

Chlorides

Marine environments are subject to chloride attack resulting from the deposition of fine droplets or crystals formed by evaporation of spray that has been carried by the wind from the sea. The quantity of chloride deposition from marine environments is directly proportional to the distance from the shore. This is due to the fact that deposition droplets and crystals are filtered off when the wind passes through vegetation or they settle by gravity.

The gaseous HCl (hydrogen chloride) is quite soluble in water and forms hydrochloric acid which is extremely corrosive.

Combustion of chemical wastes (from coal burning and municipal incinerators) produces such pollutants as HCl, chlorine, hydrogen fluoride and hydrogen bromide. When organophosphorus compounds are incinerated, corrosive phosphorus compounds are produced. Chlorides are also a product of municipal incinerators.

In addition to these general air contaminants, there may also be specific pollutants found in a localized area. These may be emitted from a manufacturing operation on a continuous or spasmodic basis and can result in a much more serious corrosion problem than that caused by the presence of the general atmospheric pollutants. Because of these varying conditions, a material that is resistant to atmospheric corrosion in one area may not be satisfactory in another. For example, galvanised iron is perfectly suitable for application in rural atmospheres, but it is not as resistant when exposed to industrial atmospheres [39].

2.2.3 Geographic location

Geographic location plays an important part in atmospheric corrosion because corrosion rates are affected by local conditions. Hence, atmospheres can be divided into the following categories:

- Rural
- Urban
- Arctic
- Tropical
  - Wet
  - Dry
- Industrial
- Marine

For all practical purposes, the more rural the area, with very dry climatic conditions or with little or no heavy manufacturing operations, the less will be the problems of atmospheric corrosion.

The air in industrial regions is laden with various sorts of contaminants, resulting from the burning of fossil fuels, hazardous waste products, road traffic, and energy production.

Combustion of fossil fuels and hazardous waste products should produce only carbon dioxide, water vapor, and inert gas as combustion products. But this is seldom the case. Depending upon the impurities contained in the fossil fuel, the chemical composition of the hazardous waste materials incinerated, and the combustion conditions encountered, a multitude of other compounds may be formed.

2.2.4 Effect of climatic conditions on corrosion

As stated previously, atmospheric corrosion is an electrochemical process that depends upon the presence of an electrolyte. Water, resulting from rain, dew, fog, melting snow, or high humidity, is the usual electrolyte associated with atmospheric corrosion. Because an electrolyte is not always present, atmospheric corrosion must be considered a *discontinuous* process [39].

Time of wetness

Corrosion takes place during the time of wetness (TOW). This phrase refers to the period during which the surface is covered by a film of water (electrolyte) that permits appreciable corrosion to take place.

The TOW is dependent upon the frequency of rain, fog, dew, the temperature of the air, relative humidity of the atmosphere, the wind speed, and the hours of sunshine. For corrosion, the temperature of the metal is also a factor [39].

Adsorption

Adsorption of water on the metal surface may be the result:

- of the relative humidity of the atmosphere,
- of the chemical and physical properties of the corrosion products,
- of the properties of materials deposited from the air, or
- a combination of all three.

Industrial atmospheres contain suspended particles of carbon, carbon compounds, metal oxides, sulfuric acid, sodium chloride, and ammonium sulfate, to mention just a few. When these substances combine with moisture or when, because of their hygroscopic nature, they form an electrolyte on the surface, corrosion is initiated.

Adsorption will occur above what is known as the *critical relative humidity*, which corresponds to the vapor pressure above a saturated solution of the salt present. The amount of water on the surface has a direct effect on the corrosion rate.

Precipitation (wetting): forming phase layers in corrosion process

Phase layers are the result of the formation of dew by condensation on a cold metallic surface, precipitation in the form of rain or fog, and wet or melting snow. The rate of corrosion will be dependent upon the concentration and nature of the corrodants in the electrolyte, which will vary depending upon the deposition rates, frequency of wetting, drying conditions, and degree of rain protection provided. If the surface is wetted after a long dry spell during which there has been a large accumulation of surface contamination, the corrosion rate will be greater than for a smaller amount accumulated during a shorter dry period. Corrosion will also be affected by the quantity of electrolyte present.

Dew

Dew is an important cause of atmospheric corrosion – more so than rain – and particularly under sheltered conditions. Dew forms when the temperature of the metal surface falls below the dew point of the atmosphere. This can occur outdoors during the night when the surface temperature of the metal is lowered as a result of radiant heat transfer between the metal and the sky. It is also quite common for dew to form during the early morning hours when the air temperature rises faster than the temperature of the metal.

The high corrosivity of dew is a result of several factors.

1. Relatively speaking, the concentration of contaminants in dew is higher than in rain water, which leads to lower pH values. Heavily industrialised areas have reported pH values of dew in the range of 3 or lower.
2. The washing effect, which occurs with rain, is usually slight or negligible.

With little or no run off, the pollutants remain in the electrolyte and continue their corrosive action. As the dew dries, these contaminants remain on the surface to repeat their corrosive activity with subsequent dew formations.

Rain

Rain has the ability to either increase or decrease the effects of atmospheric corrosion, depending upon conditions. Corrosive action is increased by rain because a phase layer of moisture is formed on the metal surface. This activity is increased when the rain washes corrosion promoters, such as H^+ from the air.

Rain has the ability to decrease corrosive action on the surface of the metal as a result of washing away the pollutants that had been deposited during the preceding dry spell.

Whether the rain will increase or decrease the corrosive action is dependent upon the ratio of deposition between the dry and wet contaminants. When the dry-period deposition of pollutants is greater than the wet-period deposition of sulphur compounds, the washing effect of rain will be dominant and the corrosive action will be decreased.

In areas where the air is not as heavily polluted, the corrosive action of the rain will assume a much greater importance because it will increase the corrosion rate.

Fog

In areas that have an appreciable degree of air pollution, high acidity and high concentrations of sulfate and nitrate will be found. The pH of fog water has been found to be in the range of 2.2 to 4.0 in highly contaminated areas. This leads to increased corrosivity.

Temperature

The effect of temperature on atmospheric corrosion has not been the subject of many studies. It appears that the effect of temperature is greater on the atmospheric corrosion of carbon steel than on other metals. An increase in temperature accelerates corrosive attack by increasing the rate of electrochemical and chemical reactions and of the diffusion process. Consequently, under constant-humidity conditions, a temperature increase will promote corrosion.

Conversely, an increase in temperature can also cause a decrease in the corrosion rate by causing a more rapid evaporation of the surface moisture film. This reduces the time of wetness, which in turn, decreases the corrosion rate. In addition, as the temperature is increased, the solubility of oxygen and other corrosive gases in the moisture film is decreased. When the air temperature falls below 0°C the electrolytic film may freeze. This freezing causes a decrease in the corrosion rate, which is typical of atmospheric corrosion rates in arctic and subarctic regions.

In general, temperature is a factor influencing atmospheric corrosion rates, but it is of importance only under extreme conditions. It has little effect on the atmospheric corrosion rate when materials are subjected to long term exposure in a temperate climatic zone [39].

Dust

The primary contaminant of air, on a weight basis, in many locations is dust. When in contact with metallic surfaces and combined with moisture, this dust can promote corrosion by forming galvanic or differential aeration cell that, because of their hygroscopic nature, form an electrolyte on the surface. This is particularly true if the dust consists of water-soluble particles or particles on which sulphuric acid are adsorbed. Dust-free air, therefore, is less likely to cause corrosion.

2.3 CORRELATION: INSULATOR POLLUTION VERSUS CORROSION

This section highlights the similarities and differences between the insulator pollution and corrosion process.

Table 2.2 is a very simplistic comparison of the corrosion and insulator pollution process.

Table 2.2: Comparison between the corrosion and insulator pollution process

	Corrosion Process	**Insulator Pollution Process**	**Comments**
1.	Electrolyte: must be present	Electrolyte: must be present	Both processes takes place during the *time of wetness*[1)].
2.	An area (or region) on a metallic surface with a negative charge in relation to a second area (i.e. anode and cathode)	Potential difference on insulator surface (i.e. to allow current flow)	Both processes require a potential difference (i.e. a positive and negative potential or anode and cathode)
3.	Rate of corrosion depends on the potential difference (galvanic cell and electrolyte); the further apart on the galvanic series - the faster the rate of corrosion	Leakage current is determined by the resistance (electrolytic pollution layer) and supply voltage; dry band formations lead to arcing, and eventual flashover	The magnitude of current flowing in either processes determine the rate at which the process develop (i.e. either slow and discontinuous or fast and continuous) leading to eventual failure

[1)] *Time of wetness* (TOW) refers to the period during which the surface is covered by a film of water (electrolyte) that permits appreciable flow of electricity.

2.3.1 Similarities

A few basic similarities are amplified as follows:

- It is evident that both processes rely on an *electrolytic conductor* to sustain the flow of current.
- The *flow of current* (electricity) is the catalyst that initiates the process. The magnitude of current flow is equivalent to the severity or rate of the process. In the case of the insulator pollution process, the leakage currents increase as a result of dry bands (high resistance) leading to increased arcing and eventual flash over. For corrosion, the increased current is a result of wetting and the chemical composition of the electrolyte, causing faster degeneration of the metal (anode).

- A *voltage* must be produced to allow the flow of current. For the insulator pollution process, the supply voltage causes the voltage gradient across the surface (or parts of the surface); in the case of the corrosion process, the gradient can be developed by the galvanic cell (bi-metallic cell) or an electrochemical cell (on the surface of one piece of metal to another part of the same metal).
- The *rate of the process* is determined by the *contaminants* present, the type (surface) of the *material*, and the *environmental and climatic conditions*.

Note: The environmental conditions (pollutants), climatic conditions (wetting), the voltage, and the material (type of metals) are all factors that determine the corrosion rate (and corrosion category). The same factors also determine insulator pollution severity levels (i.e. rate at which leakage current develop into an arc).

The following conditions were identified as having an influence, some to a greater extend than others, on both the insulator pollution and corrosion process and are amplified as follows:

- geographic location (i.e. marine, industrial and desert),
- Climatic conditions
  - time of wetness (TOW),
  - adsorption,
  - climate factor (wetting) and precipitation,
  - dew,
  - rain (i.e. increase or decrease activity),
  - fog,
  - temperature, and
- contaminants (i.e. SO_2, NO_x and chlorides – NaCl).

The local climatic conditions inevitably affect both the insulator pollution and corrosion process, one can almost say, in very much the same way. This statement is verified with results from various test sites (see chapter 6).

One of the primary factors that affect both the corrosion and insulator pollution (leakage current) process is the time-of-wetness (TOW – water film on surface). In the corrosion process the TOW results in higher current flow between the anode and cathode, resulting in

a faster corrosion rate. In the case of insulator pollution, the TOW leads to higher leakage current activity; depending on the type of material, this can result in ageing and deterioration, and in the extreme case, flashover can occur.

2.3.2 Differences

The following differences between the corrosion and insulator pollution process is worth noting, see Table 2.3.

Table 2.3: Differences between the corrosion and insulator pollution process

	Corrosion Process	Insulator Pollution Process	Comments
1.	Metal surface: must be present	Insulator material: Glass, ceramic, Polymers	Corrosion takes place on a metallic surface, while an insulator material can be of one of several types.
2.	No external voltage source: Chemical (metal and non-metallic recipient) or electrochemical (bi-metallic) reaction	Voltage source required: electrochemical cell is formed on the insulator surface (two electrodes at different potential) and the electrolyte.	For the corrosion process no external power source is required, while the insulator flashover process develops using the applied voltage.
3.	Impact over time: Damage is noticeable over a long period (days, months or years).	Impact is immediate: the pollution flashover process can develop very quickly and the impact is immediate	Damage from the corrosion process develops over time, while the insulator pollution flashover has an immediate impact - power loss, etc.

Some of the key differences between the corrosion process and the insulator pollution flashover are amplified below.

- For corrosion, a metallic surface must be present, whereas, the insulator flashover process can take place on any insulator surface (glass, ceramic, polymers).
- No external voltage source is required for the corrosion process, while the insulator flashover process requires a voltages source.
- The impact of the damage from the corrosion process develops over an extended time (days, months, years), whereas impact from an insulator flashover is immediate (although development could have been over time).

2.4 CONCLUDING REMARKS

It was shown that there are similarities and differences between the corrosion and insulator pollution process.

The major similarities can be summarised as follows:

- a conductive electrolyte must be present,
- a voltage gradient must be developed that initiates current flow,
- current flow can be seen as the driving force behind the process, and
- environmental conditions (pollutants), climatic conditions (wetting), and the type of material determine the rate at which the process develop.

The major differences are provided below.

- the corrosion process requires a metallic surface to operate, whereas the insulator flashover process can take place on any insulator surface (glass, ceramic, polymers),
- no external voltage source is required for the corrosion process, while the insulator flashover process requires a voltages source, and
- the impact of damage from the corrosion process (i.e. metal degradation) develops over an extended time (days, months, years), whereas impact from an insulator flashover is immediate (i.e. an electrical outage).

3

TEST METHODOLOGIES

This chapter describes the measurement techniques that were utilised to determine atmospheric pollution severity levels in respect of insulator pollution and corrosion.

The test methodologies, descriptive equations and related pollution severity levels are given for DDG, ESDD, and corrosion test methods (CLIMAT and metal specimens). The reader should be able to execute any of the abovementioned test protocols at a test site.

3.1 INSULATOR POLLUTION TESTS

Background

The IEC 60815 document is a guideline for the selection of insulators. This document defines:

- pollution levels,
- provides an approximate description of typical corresponding environments, and
- assigns a corresponding minimum specific creepage distance (mm/kV).

This document was therefore seen as the ideal starting place for the investigation into a test methodology to compile an insulator pollution severity map. Using the guidelines as set out by IEC 60815, a reference point was established for:

- the **classification** of insulator pollution environments (in respect of the environmental and climatic conditions), and
- a minimum **specific creepage distance** (in respect of the pollution classification).

Excerpts from the IEC 60815 guideline [3] are reproduced below for the purpose of laying a foundation for the following sections.

IEC 60815 guideline

The aim of the guide is to give *simple general rules that should assist in choosing the insulator, which should give satisfactory performance under polluted conditions.* These rules are based upon *minimum creepage distance* requirements. They provide an easily accomplished way to choose insulators based on the predicted severity of the site where these insulators are to be installed [3].

This IEC 60815 guideline describes the method of insulator selection based on two criteria:

- evaluating qualitatively severity of the pollution of the site, and
- choosing insulator dimensions with regard to the specific nominal creepage distance.

NOTE: It is worth emphasizing the fact that the IEC 815 guideline is based on the principle that ***the site pollution is known*** *or that* ***sufficient experience of insulator performance*** *in a region has been gained.*

Evaluation of the pollution site

Table 3.1 provides the pollution indices for dust gauges (DDG) and equivalent salt deposit density (ESDD) tests as prescribed by the Round Robin Pollution Monitor Test Protocol [1], [3].

IEC 60815 defines four levels of pollution: light, medium, heavy and very heavy. Table 3.2 provides a pollution level with an approximate description of some typical corresponding environments [3].

Two direct methods of Insulator pollution measurements were utilised: directional dust deposit gauges (DDG) and equivalent salt deposit density (ESDD) measurements as prescribed by the "Round Robin Pollution Monitoring Study Test Protocol", of the CIGRE task force 33.04.03 [1]. The methods are discussed below.

Table 3.1 Pollution Indices in respect of pollution class

Pollution Class	CD[1] (mm/kV[2])	DDG Pollution index (µS/cm)	ESDD Pollution index (mg/cm^2)
I - Light	16	0 – 75	0.03 – 0.06
II - Medium	20	76 – 200	0.10 – 0.20
III – Heavy	25	201 – 350	0.30 – 0.60
IV – Very Heavy	≥ 31	>350	> 0.80

[1] Minimum nominal specific creepage distance.
[2] Ratio of the leakage distance measured between phase and earth over the r.m.s. phase to phase value of the highest voltage for the equipment.

Table 3.2: IEC 60815 site evaluation

Pollution level	Examples of typical environments
I. Light	▪ Areas without industries and with low density of houses equipped with heating plants ▪ Areas with low density of industries or houses but subjected to frequent winds and/or rainfall ▪ Agricultural areas[1] ▪ Mountainous areas All these areas shall be situated at least **10 km to 20 km from the sea** and shall not be exposed to winds directly from the sea[2]
II. Medium	▪ Areas with industries not producing particularly polluting smoke and/or with average density of houses equipped with heating plants ▪ Areas with high density of houses and/or industries but subjected to frequent winds from and/or rainfall ▪ Areas exposed to wind from the sea but not too close to the coast (at least several kilometres distant) [2]
III. Heavy	▪ Areas with high density of industries and suburbs of large cities with high density of heating plants producing pollution ▪ Areas close to the sea or in any case exposed to relatively strong winds from the sea [2]
IV. Very heavy	▪ Areas generally of moderate extent, subjected to conductive dusts and to industrial smoke producing particularly thick conductive deposits ▪ Areas generally of moderate extent, very close to the coast and exposed to sea-spray or to very strong and polluting winds from the sea ▪ Desert areas, characterized by no rain for long periods, exposed to strong winds carrying sand and salt, and subjected to regular condensation

[1] Use of fertilizers by spraying, or the burning of crop residues, can lead to a high pollution level due to dispersal by wind.
[2] Distances from the sea coast depend on the topography of the coastal area and on the extreme wind conditions.

3.1.1 Directional dust deposit gauge (DDG)

Background

The DDG was developed in the United Kingdom. The dust gauge was used in the first insulator pollution survey that was conducted in South Africa. The DDG is a simple and inexpensive method to classify a site according to the amount of conductive pollution. The gauge is a passive device that requires no external power source, making it very practical to use [5], [13].

Construction

The DDG consists of four vertical collection tubes with slots milled in the sides. The four slots face the four cardinal points of the compass: North, East, South, and West as shown in figure 3.1.

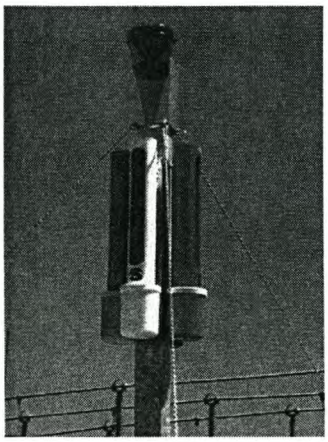

Fig. 3.1 Directional dust deposit gauges

Four removable containers are attached to the bottom of each tube. Dust deposits are blown into the tubes via the slots and are collected in each container.

Contaminant collection

The four gauges measure the amount of pollution deposit equivalent to that of insulator from each main wind direction. The gauge is designed primarily to collect wind deposit rather than gravity deposit since the former is the main cause of pollution deposit on vertical insulator strings. The gauge is more prone to collect coarser particles than the

finer, lighter particles. The collecting efficiency is high if the wind blows directly into the slot and decreases as the wind direction approach right hand angles with the slot. The effect of the slight loss of sample product is considered negligible. Practically, high winds will result in the removal rather than the deposit of pollutant on the insulator surface.

An insulator undergoes the process of natural washing due to rain and therefore loses some of the pollutant deposits. The DDG reading is therefore not a direct reflection of the dust deposit on an insulator. It is rather an indication of the accumulative pollutant severity level in an area that an insulator is exposed to during one test period [13].

Installation

The dust gauges were mounted 3 m above the ground level, see Appendix D for detail. Theoretically, the gauges should be mounted at the same height as the insulators to achieve the same amount of exposure to wind-borne deposits. Practically, this is unsafe and difficult. At the day of installation the gauge must be labeled with the date, prevailing wind direction and name of the test site.

Sampling (measurements)

The containers were normally removed after a 30-day exposure period (and replaced with new ones) and the conductivity of each was measured.

A detailed description of the method to perform DDG measurements is given below:

- Distilled water is added to the contents of the container until the total volume equals 500 ml. The volume conductivity of the distilled water should not exceed 5 µS/cm. If the bottle already contains some rainwater, then the volume can be normalised to 500 ml (or 1000 ml) [19]. It was proven that a volume of 500 ml of distilled water is the minimum required to dissolve all salts [13].
- Record the total volume of liquid (including the distilled water) for each container.
- Measure the volume conductivity (µS/cm) for each container with a meter automatically temperature compensated to 25 °C. Conductivity measurements are affected by the water sample temperature.

- Record the number of days since the previous test. This period should not be less than 20 or more than 40 days.
- Clean the bottles for re-use during the next sampling period.

Calculations

The *pollution index* is defined as the *mean value of the conductivities of all four directions*, expressed in µS/cm and arithmetically normalised to a 30-day month.
The equation to calculate normalised DDG conductivity is:

$$\sigma_N = C\,(V/500) \cdot (30/N) \tag{3.1}$$

where σ_N : normalised conductivity (µS/cm)
C : volume conductivity (µS/cm), $C = C_{measured} - C_{added}$
V : volume of distilled water (ml)
N : amount of days since previous removal of the containers

NOTE: The volume conductivity, C, is the difference between the conductivity measurement (after it was mixed with the pollutants in the container) and the added water.

The average conductivity for the four directions (north, east, south, west) is used as a final conductivity result as shown in the next equation:

$$Average\ \sigma = (\sigma_N + \sigma_E + \sigma_S + \sigma_W) / 4 \tag{3.2}$$

A pollution classification is then assigned for a DDG using the pollution index as defined by the Round Robin Test Protocol [1], Table 3.1.

3.1.2 Equivalent salt deposit density (ESDD)

Background

The actual pollution on insulators is usually referred to as the amount of dissociable matter present, defined as the amount of sodium chloride (NaCl) that gives the same electrical conductivity as the pollutant when dissolved in a given quantity of distilled water divided by the area of the washed surface [18]. The severity of the contamination layer is expressed in terms of the equivalent salt deposit density value (ESDD). The ESDD, however, only states the steady-state solubility of the solution and not the rate at which the salt goes into solution. The ESDD values are expressed in mg/cm^2.

Construction

A unit string, consisting of seven glass disks, is used for the ESDD measurements. In the light of the fact that the U120BS glass cap and pin insulators are used extensively in the South African transmission grid, it was decided to install a similar, single seven-unit string for the ESDD tests (see figure 3.2).

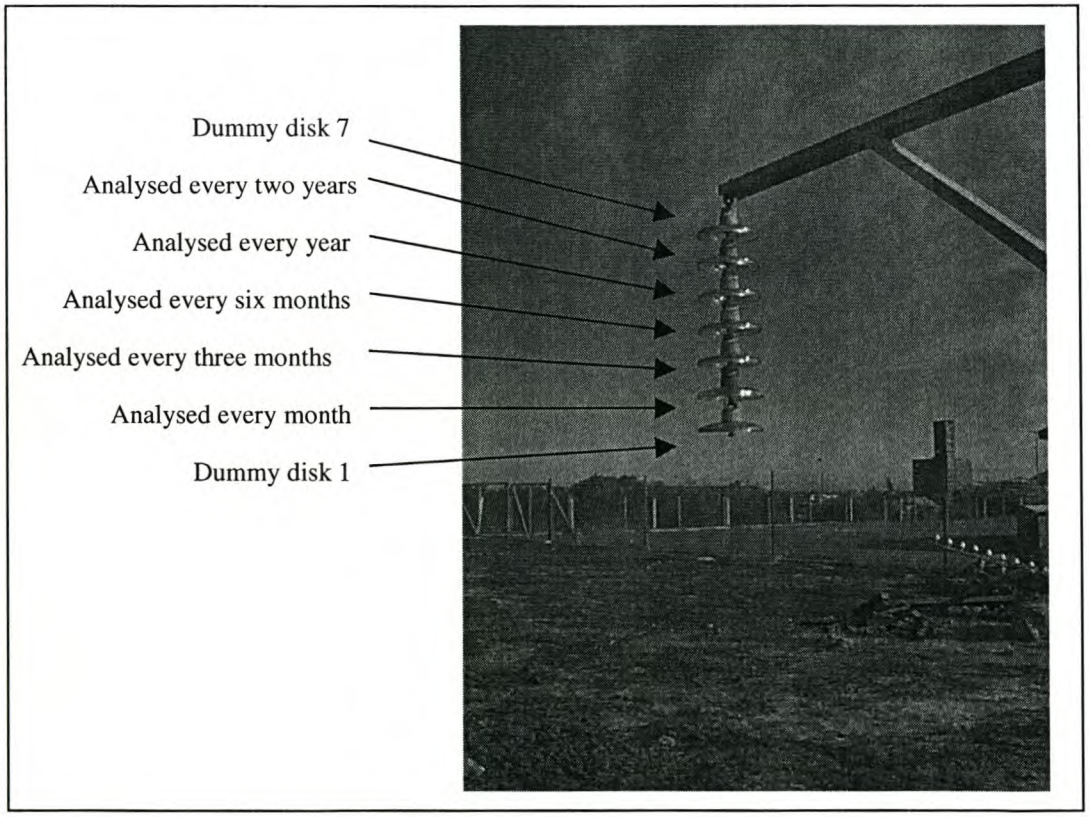

Figure 3.2 ESDD test string

Installation

The unenergised insulator string is located at a height as close as possible to that of the line or busbar insulators. Prior to installation, the insulators should be washed with methylated spirits, trisodium phosphate or other detergents to remove all traces of dirt and grease. The caps and pins must also be rid of any rust or deposits. If corrosion is a problem, the metal parts can be painted with a salt-water resistant paint to avoid wash-down of corrosion particles onto the glass. The best results are obtained if the disks are washed with warm water (50°C) and then rinsed with distilled water. The surface is clean and free of grease if a large continuous water film is observed. After cleaning, the string must be installed, without touching the glass parts.

Sampling (measurements)

Each disk of the insulator string is monitored at a defined interval (see figure 3.2):

- Disk 1: every month
- Disk 2: every three months
- Disk 3: every 6 months
- Disk 4: every 12 months (each year)
- Disk 5: every 24 months (every two years)

The top and bottom dummy insulators are not tested and are used to eliminate the end effects on a total string.

The general technique for measurements of ESDD involves dissolving the surface deposits in a known quantity of distilled water (2 litres) with a low conductivity (<5 μS/cm). The principle of ESDD measurements is explained as follows:

- The glass surfaces of the discs should not be touched to avoid any loss of pollution.
- Cover the cap and pin respectively with tin foil without covering the glass surface.
- Measure down one litre of distilled water (1 – 2 μS/cm) and pour into a bowl.
- Place the test insulator on its foil-covered cap in the water and wash the top surface with gentle hand strokes without any wash water wetting the bottom surface (ribbed profile).

- After the top surface has been washed, gently shake off any remaining water on the tin foil, remove the insulator from the bowl and pour water into a container. Take care that all deposits are removed from bowl.
- Rinse bowl before the commencement of next test.
- Measure down one litre of distilled water (1 – 2 µS/cm) and pour into bowl.
- Place the same insulator as mentioned above on its cap in the bowl and gently wash pollution off the bottom surface (ribbed profile) with your hands.
- Pour water in second container taking care again that no deposits remain in the bowl.
- Swirl water content in containers to ensure that salts are totally dissolved prior to measuring.
- Measure the volume conductivity (µS/cm) with a meter automatically temperature compensated to 25 °C.

Calculations

The ESDD in mg/cm^2 is obtained from the measurements of the volume conductivity, solution temperature, and volume of the wash water. The conductivity probe measures the volume conductivity, σ_t, at ambient solution temperature t.

The measurement is then normalised to a standard 25 °C reading using the following equation:

$$\sigma_{20} = \sigma_t \ [1 - 0.02277(t - 20)\, e^{-0.01956(t-20)}] \tag{3.3}$$

where σ_t : measured volume conductivity (µS/cm)

t : solution temperature (°C)

σ_{20} : volume conductivity corrected to 20 °C

The salinity, S_a (kg/m^3), of the suspension at 20 °C is obtained with equation:

$$S_a = (5.7 * \sigma_{20})^{1.03} \tag{3.4}$$

The equivalent salt deposit density (ESDD) in mg/cm^2 is then determined with equation:

$$ESDD = (S_a * V_d) / A_{ins} \quad (3.5)$$

where V_d : volume of distilled water (cm^3) used

A_{ins} : area of the washed insulator (cm^2)

The surface areas of the test insulators are:

U120BS : 827 cm^2 (top) and 1440 cm^2 (bottom)

Once the ESDD value is calculated, the pollution severity can be established (Table 3.1).

NOTE: The above equations are relevant if the solution temperature ranges between 5 and 30 ℃ and is in the range of 40 to 4000 μS/cm [13].

3.2 ENVIRONMENTAL CORROSION TESTS

The corrosion process and the effects of atmospheric pollution and climatic conditions were discussed in chapter 2 (section 2.2).

Two methods of Environmental Corrosion Measurement (ECM) techniques were used in this study: metal and wire-on-bolt (CLIMAT) test specimens. All measurements were performed in accordance with the procedures as prescribed by the American Society for Testing and Materials (ASTM) and the International Organisation for Standardisation (ISO) [23 – 33], [35 – 38].

3.2.1 Selecting the test method

Background

Many methods of air-quality measurements have inherent averaging times. In selecting methods for measuring air quality or assessing air pollution effects, this fact must be borne in mind. Thus an appropriate way to assess the influence of air pollution on metals is to expose identical specimens at different locations and compare their annual rate of corrosion among several locations [22].

The **main factors** that influence the corrosion process can be summarised as follows:

- The nature of the metallic material (i.e. alloy-making processes, chemical composition, mechanical and thermal treatments, condition of surfaces, etc.).
- The environment (i.e. chemical composition, temperature, humidity, winds, etc.).
- The operational conditions (i.e. mechanical stresses, protective coatings, etc.).

3.2.1.1 Standards and classification

As mentioned above, the method that was selected for the atmospheric corrosion study was based on the *weight loss* principle for test specimens as prescribed by ISO 9223, 9225, 9226, and ASTM G116, G50 standards [35], [37], [38], [24], [25].

Table 3.3 lists the major ISO and the equivalent ASTM standards that were reviewed for this study; a combination of ASTM and ISO practices was employed. Table 3.4 shows the corrosivity classification for both ISO and ASTM. ISO 9223 classify five categories of corrosivity [35]. The ASTM G116 Practice assigns a galvanic effect (GE) in percentage for each corrosivity category [24].

Table 3.3: List of ASTM and equivalent ISO standards

Description of standard	ASTM	ISO
Practice for preparing, CLEANING, and evaluating corrosion test specimens	G1	8407
Guide for applying STATISTICS to analysis of corrosion data	G16	
Practice for Conducting atmospheric Corrosion tests on metals	G50	9226
Practice for conducting Wire-On-bolt test for atmospheric corrosion	G116	9226
Practice to characterise or monitor the atmospheric site during testing	G84, G91, G92	9225
Classification of atmospheric corrosivity		9223

Table 3.4: ISO and ASTM atmospheric corrosion categories

Corrosivity	ISO Index	ASTM (G116) GE (%)
Very low	C1	0 – 20
Low	C2	21 – 40
Medium	C3	41 - 60
High	C4	61 – 80
Very High	C5	81 - 100

3.2.1.2 Test Methods

Three test methods are discussed below.

Method A: Metal exposure tests – Weight loss

The methods available to study atmospheric corrosion fall into three categories:

- Exposure of metallic samples to an operational environment followed by determination of weight loss and by a thorough macro- and microscopic visual inspection.
- Accelerated non-electrochemical corrosion methods.
- Electrochemical methods.

Method B: Monitoring tests

It is also recommended that ***atmospheric classification*** be performed by "Measurement of Time-of-Wetness (TOW)" [29] or by "Monitoring atmospheric SO_2, using the sulfation plate technique" [30], see chapter 6 (section 6.2.5.1) for more detail.

Method C: Metal exposure tests – volume loss

Another method to determine the corrosion rate is to determine the ***area (volume) loss*** of the metal [25].

Summary of corrosion test method

A detailed description of the cleaning procedure and the corrosion test method is provided in Appendix H. A summary is provided below [23], [26]:

- cleaning of test specimens before exposure,
- weighing of test specimens before exposure (original mass),
- exposing specimens at test site (duration is determined by type of test),
- cleaning of test specimens after exposure,
  - three methods of cleaning can be used: mechanical, chemical, and electrochemical
- weighing of test specimens after exposure (final mass), and
- assigning a corrosion classification (record the type of corrosion attack, i.e. pitting).

*Note: Only Method A (**exposure of metallic samples**) was used in this study.*
Method B was not performed due to project time constraints.
Method C was not performed due to the complexity and high degree of variance in test results associated with this method [25].

3.2.2 CLIMAT (wire-on-bolt) test

The wire-on-bolt test is also referred to as the CLIMAT (**CL**assify **I**ndustrial and **M**arine **AT**mosphere) test [24]. For the CLIMAT test; preparation, testing and analysis were done as prescribed by ASTM G116 [24] and ISO 9226 [38]. In principle, this test method is a galvanic corrosion (or dissimilar metal) effect.

This method consists of wrapping aluminium wire (anode material) around the threads of a bolt or threaded rod (cathode material), Figure 3.3 is a photograph of an actual completed CLIMAT assembly just before exposure. The mass of the wire (after exposure) is then determined and a pollution classification assigned.

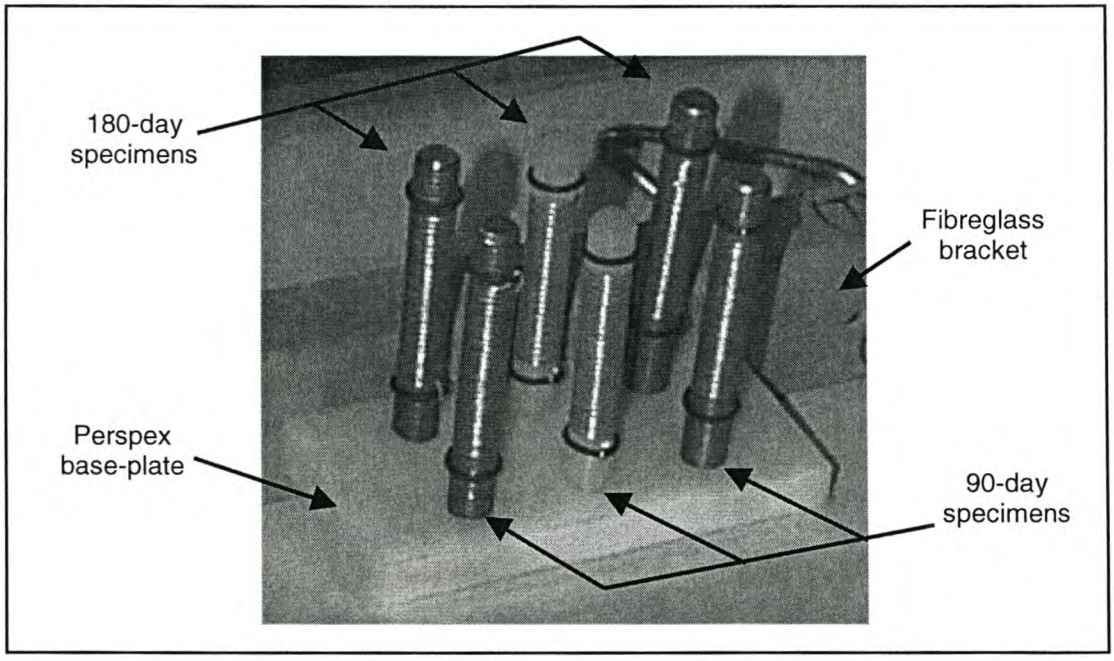

Fig. 3.3 CLIMAT specimens for 90 and 180-day exposure
Mild steel rod, Reference (non-conductive) rod, Copper rod

Construction

The CLIMAT test was performed on two types of cathode material, copper (Cu) and mild steel (Fe). A *reference specimen* of the anode wire on a non-conductive threaded rod (nylon rod) was used to separate general and crevice corrosion effects from galvanic corrosion effects [24].

The cathode material (i.e. Cu and Fe) was chosen as a 12 mm diameter threaded rod and it was cut to 100 mm lengths. The anode material (aluminium wire) was cut to 1 m lengths.

The process of making the assemblies is described below:

- All the parts were thoroughly cleaned and degreased [23].
- The mass of each wire was determined to the nearest 0.0001g [24].
- The wire was tightly wrapped around the threaded rods.
- Rubber O-rings were used to secure the ends of the wire to the rods. Small bolts of the same type of material as the rod material, or nylon or stainless steel insulated with nylon, may be used [24].
- The rod assemblies were then inserted into a non-conductive base-plate (i.e. Perspex).
- The base-plate was then mounted horizontally onto a bracket.
- Each assembly was then installed at the predetermined test site location.

Exposure duration

Two test periods were used, a 90- and a 180-day exposure period. It is worth mentioning that a 180-day exposure is not necessary in terms of international standards (ASTM and ISO), however, it was the author's objective to determine whether a significant difference is noted over a longer exposure period.

It is recommended by ASTM Practice G116 that three test sets (three Cu, Fe and non-conductive rods) be prepared for each monitoring site. Each set must be exposed for 90 days and replaced with another set, thereby totalling a 270-day exposure. The average mass loss is then used to classify the monitoring site. Depending on the material combinations and corrosivity of the atmosphere, longer or shorter exposure durations may be needed to get measurable mass loss or to prevent loss of the wire during exposure [24].

Calculations and interpretation of results

In this study both the ASTM G116 [24] and the ISO 9226 [38] calculation methods were used to determine the rate of corrosion. Appendix G provides the corrosion test results.

ISO calculation: CLIMAT test

The ISO equation for the corrosion rate in mirometers per year (μm/a) is given as [38]:

$$r_{corr} = 0.25 \text{ x } \Delta m \cdot d / (m \cdot t) \tag{3.6}$$

where Δm : is the mass loss (mg) of the wire

d : is the wire diameter (mm)

m : is the original mass (grams) of the wire

t : is the exposure time (in years)

ASTM calculation: CLIMAT test

The ASTM equation to calculate corrosion rate in milligrams per meter (mg/m) is given as [24]:

$$\Delta m_m = \Delta m \cdot m \tag{3.7}$$

where Δm : is the mass loss (mg) of the wire

m : is the original mass (mg) of the wire

To normalise the mass loss to 90 days, the following equation is used [24]:

$$ML_{90} = (\Delta m_m / d)\ 90 \tag{3.8}$$

where ML_{90} : is the mass loss (mg/m) normalised to 90 days

d : is the exposure period in days

Test results are provided in Appendix G and chapter 6 and 7.

3.2.3 Metal specimen test

The metal coupon test was based on the principles of the ASTM G50 [25] and ISO 9226 [38] standards. The preparation and cleaning was done as prescribed by ASTM Practice G1 [23].

Standard specimens of galvanised steel, mild steel and aluminium were mounted on a non-conductive bracket (fibreglass) and exposed to the atmosphere for a predetermined duration (average 220 days). The installations were oriented to face a westerly direction, Atlantic Ocean (marine pollution source).

Figure 3.4 is a photograph of an actual completed metal coupon assembly installed on 120m high weather mast at the Koeberg Weather station.

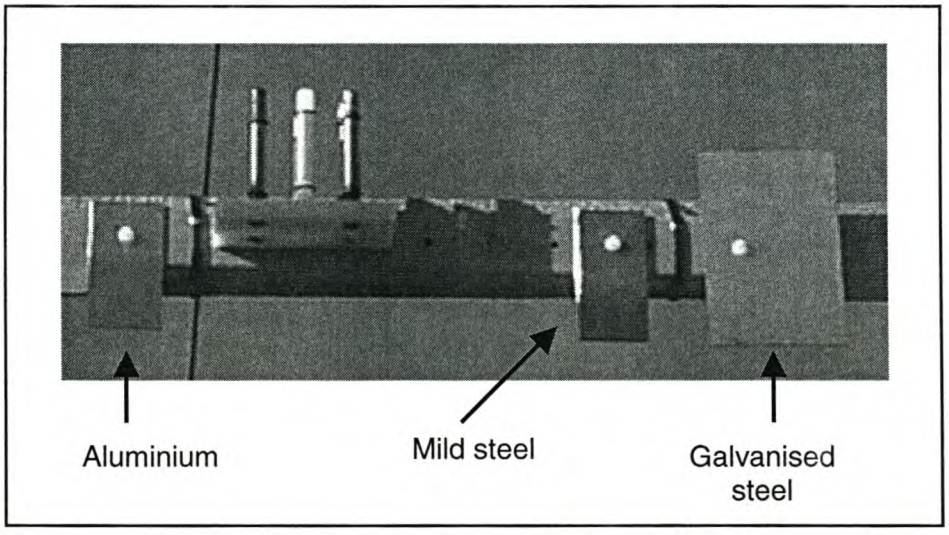

Fig. 3.4 Metal specimens mounted on a fibreglass bracket (Aluminium, mild steel, galvanised steel)

Construction

The metal coupon specimen dimensions are given as follows:

- Mild steel : 100 x 50 x 3 mm
- Galvanised steel : 150 x 100 x 1 mm
- Aluminium : 100 x 50 x 5 mm

The process of preparing and installing the specimens is described below:

- All the parts were thoroughly cleaned and degreased [23].
- The mass of each specimen was determined to the nearest 0.01g [25].
- The completed assemblies were attached to a non-conductive bracket using nylon bolts and nuts.
- Each assembly was installed at the predetermined test site locations.
- After exposure, each specimen was visually inspected, ASTM G33 [26].
- Each specimen was cleaned, only mechanical cleaning (scrubbing with a non-metallic brush) was performed.
- Each specimen was then weighed to obtain the final mass.

Exposure duration

The metal coupons were exposed for an average of 220 days (0.6 years).

Calculations: Metal coupons

The ISO 9226 [38] standard provide two equations to calculate the corrosion rate for metals:

1) The corrosion rate, r_{corr}, in mirometers per year (µm/a) is given as:

$$r_{corr} = \Delta m \,/ (A \cdot \partial \cdot t) \tag{3.9}$$

where Δm : is the mass loss (mg)

A : is the surface area (m^2))

t : is the exposure time in years

∂ : is the density in gram per cubic centimetre (g/cm^3)

$\partial_{Fe} = 7.86$ (g/cm^3)

$\partial_{Zn} = 7.14$ (g/cm^3)

$\partial_{Cu} = 8.96$ (g/cm^3)

$\partial_{Al} = 2.70$ (g/cm^3)

2) The corrosion rate, r_{corg}, can also be expressed in grams per square meter year [g/(m^2·a)] given as:

$$r_{corg} = \Delta m \ / (A \cdot t) \tag{3.10}$$

where the symbols have the same meaning as in the above equation.

3.3 CONCLUDING REMARKS

Chapter 3 investigated various test methodologies that can be utilised to develop a pollution severity map. For insulator pollution tests, the DDG and ESDD methods were discussed; for corrosion, the CLMAT and flat metal specimen tests were covered.

The complete testing procedure, descriptive equations and related pollution severity classifications are given for DDG, ESDD, CLIMAT, and flat metal specimens. The reader should be able to execute any of the abovementioned test protocols at a test site.

4

PRELIMINARY VERSIONS OF AN INSULATOR APPLICATION MAP

This chapter discusses two preliminary versions of the insulator pollution severity application map (IPSAM) for South Africa. The first map was based on a literature study of environmental pollution sources and climatic conditions throughout South Africa, whereas the second map was developed based on an insulator pollution questionnaire survey.

The IEC 60815 standard [3] formed the basis (reference document) of the preliminary developments as explained below.

4.1 IEC 60815 GUIDELINE

The IEC 60815 document is a *guide for the selection of insulators in respect of polluted conditions* [3]. A detail review of this document was given in chapter 3, section 3.1.

The selection of insulators is based on the principle that the **site pollution is known** or that sufficient experience of **insulator performance in a particular environment** has been gained [3].

The **evaluation of pollution sites** and the **classification of the pollution level** for the preliminary maps were based on guidelines specified in the IEC 60815 standard. A summary was given Tables 3.1 and 3.2 (see chapter 3, section 3.1).

4.2 BUILDING THE MAPS

Appendix A and B shows the phase one and two Insulator Pollution Severity Application Maps (IPSAM) respectively. The approach was to divide the country into ESKOM's technical service areas (TSA) and to assign a corresponding colour-code according to the highest pollution severity recorded for the TSA. The map also displays areas with heavy agricultural and industrial activity, denoted by the symbols Ⓘ and Ⓐ respectively.

The user (design or maintenance engineer) can determine the minimum specific creepage distance applicable for a specific area (or TSA) by simply identifying the area on the map. Table 4.1 illustrates the colour codes in respect of the pollution classification.

Table 4.1: Pollution class colour code for the insulator application maps

Specific creepage distance (mm/kV)	IEC 60815 Pollution Class	Colour Code
16	Light	Light Green
21	Medium	Green
25	Heavy	Orange
>31	Very Heavy	Red

4.3 PHASE ONE MAP

As previously mentioned, the phase one map was based on a literature survey to identify all the atmospheric pollution sources, their severity, and an area of impact within the Republic of South Africa.

The study included the following criteria for South Africa [4], [5]:

- Pollution measurements: dust gauges (DDG),
- Atmospheric corrosion,
- Pollution sources (marine, industrial, and agricultural),
- Population density,
- Topography, and
- Meteorology.

4.3.1 Pollution measurements: DDG study (1980)

Macey used directional dust deposit gauges (DDG) to determine the pollution indices for 61 sites around the country over an 18 to 36 month period in a 1980 study [6].

Table 4.2 provides a summary of the pollution indices, indicating that 45% of the sites measured were classified as light, while only 8.2% recorded conductivity values in the very heavy category. The detailed information provided in Table 4.3 shows that pollution indices were very heavy in areas along the coast and regions of high industrial (coal mines) and agricultural activity (sugar cane and maize).

4.3.2 Atmospheric Corrosion

By studying corrosion rates in various areas throughout the country, it is possible to determine the density of certain harmful elements (sulphur dioxide, chlorides, saline) that are prevalent in the atmosphere. Corrosive elements include gases, soot, humidity (fog, dew, rain and snow), inert and aggressive dust. Corrosion (pollution) rates vary in rural, marine (coastal), urban and industrial environments. A map detailing corrosion rates throughout the subcontinent was produced by the CSIR and was also incorporated in the phase one map in determining pollution densities [9].

4.3.3 Pollution Sources

The three main pollution sources affecting atmospheric pollution severity levels are: marine, industrial, and agricultural pollution.

4.3.3.1 Marine Pollution

Areas up to 20 km of the coast experience a high degree of saline (NaCl) pollution. This form of pollution, depending on the topography and the climate, is particularly harmful to electrical insulation as it forms a conductive layer when it becomes wetted. It is also recognised as an extremely harmful corrosive agent. Areas along the coast were therefore classified ***very heavy*** due to the high concentration of saline.

Table 4.2: Summary of pollution indices for 61 sites in South Africa

Pollution Level	Percentage (%)
Light	45.9
Medium	29.51
Heavy	16.39
Very Heavy	8.2

Table 4.3: Summary of pollution indices for 61 sites in the RSA [6]

POLLUTION INDICES AS OBTAINED FROM DIRECTIONAL DUST DEPOSIT GUAGES			
DISTRIBUTION STATION	POLLUTION INDEX (µS/cm)	DISTRIBUTION STATION	POLLUTION INDEX (µS/cm)
Acacia	64	Klip	349
Afrex	312	Koeberg	
Amcor	122	- Constuction S/s	298
Anglo Alpha	269	- Test Site 2	160
Apex	35	- Test Site 4	1835
Ascot	111	- Live test Station	2046
Brand Four	273	Kudu	112
Camden	43	Lamplough	50
Capex	133	Lime Acres	231
Chemie	234	Mandini	66
Chivelston	40	Metalloys	63
Congella	130	Modderfontein	274
Copperton	50	Moorreesburg	61
De Hoek	582	Mtunzini	47
Delta	85	Natref	73
Droerivier	22	NCW	190
Eersterivier	49	Oakdale	60
Elgin	31	Olympus	122
Glochner	38	Onrust	80
Grassridge	53	Panvlakte	62
Hartebees Mill	95	Pembroke	28
Hex River	67	Poseidon	22
Hydra	55	Potch Munic	56
Illovo	50	Prairie	71
Impala	91	Riverview	124
Invubu	65	Saldanha	207
Jupiter	95	Sappi	51
Kariega	36	Sasol industries	102
Kelso Traction	454	Sasol Works	168
Slurry	301	Vanderbijl Blower	154
St Michaels	134	Westgate	359

4.3.3.2 Industrial Pollution

Certain industries generate harmful by-products, which are absorbed or transported via the atmosphere and later deposited as pollution on electrical apparatus. Types of pollution include highly conductive coal dust from coal mines, sulphur dioxide from Oil refineries, and other chemicals from chemical producing plants and the paper and pulp industry.

Coal mines are normally situated very in close proximity to power stations to reduce transportation costs. The negative consequence is a direct increase in conductive coal dust settling on insulating material in the power station and on electrical transmission lines, adversely affecting insulator performance. Areas with a high density of coal mines include Mpumalanga (Witbank, Middelburg, Bethal), Gauteng (Vereeniging) and the Northern Province (Ellisras). Although pollution due to coal dust can be severe, it remains a **localised problem** confined to areas in the vicinity of coal mines only.

Three sulphur dioxide (SO_2) producing oil refineries are in operation in the country and are situated at Durban, Cape Town and Sasolburg. Localised pollution problems can be expected in these areas. Chemical producing plants and paper and pulp manufacturing industries are located in all the major towns throughout the country and these may also cause **localised pollution**.

4.3.3.3 Agricultural Pollution

South Africa uses 11% of its land for crop growing. Crops that affect atmospheric pollution levels include wheat, maize and sugar cane. Problems arise from the spraying of the abovementioned crops with insecticides and other chemicals, which later interact with the environment. These chemicals form a conductive pollutant that is hazardous to High Voltage apparatus. The majority of wheat farming is performed in the Western Cape, with sugar cane grown along the entire Kwazulu-Natal coast [7]. The burning of sugar cane residue has proven to be hazardous as conductive particles are released into the air. These particles collect on the High Voltage Insulators and other electrical apparatus thereby reducing their performance.

4.3.4 Population Density

Urbanisation has seen an influx of people from rural areas into major towns and cities. Due to the high demand, electrification needs have not been met and a substantial number of households of which the majority are informal settlements, rely on coal, wood and paraffin as a energy source for cooking and heating. By-products of this heating and cooking process often form dense fog/smog at peak times (early morning and late evening). Most of these informal settlements are situated on the outskirts of major towns and the activities mentioned above, play a significant role in contributing to localised pollution problems.

4.3.5 Topography of the Area

Areas which are relatively close to the coast but are shielded by high land or mountain ranges are normally the exception, significantly reducing aerosol migration further inland. These areas are classified as *heavy* to *medium* depending on their distance from the coast.

Deserts that are situated far from the coast can be classified as *light* pollution areas, provided the pollution is non-conductive and wetting, as a result of dew formation (fog or mist), is minimal.

4.3.6 Meteorology

The climate of the area plays a significant role in aerosol migration. Some of the primary parameters that affect pollution severity levels are discussed below.

4.3.6.1 Wind

Elements such as wind speed, wind direction, rain, temperature and relative humidity all influence the type of pollution and the way in which it is deposited on the insulator surface. The size of the pollution particle that can be transported by the wind is determined by the speed of the wind. Higher wind speeds can sustain bigger particles whereas lower wind speeds result in a fine layer of pollution deposition. High wind speeds can carry harmful pollutants to areas that are relatively far from their origin (pollution sources) [13]. Coastal areas which are exposed to high wind speeds (like the Western Cape and Natal East Coast) will therefore experience high pollution severity quite far inland.

4.3.6.2 Relative Humidity

An increase in the relative humidity results in the air becoming heavier eventually leading to gravitational fall-out. Harmful particles that could be present in the air are then deposited on the insulator surface; coupled with high humidity these particles quite easily form an electrolyte, which is conductive, and results in higher leakage current activity [13], [21].

4.3.6.3 Temperature

An increase in temperature causes the pollution layer to dry out, thus minimising its harmful effects. Conversely, a decrease in temperature leads to condensation and wetting of the pollution layer, with eventual increase in leakage currents.

4.3.6.4 Temperature inversion

Phenomena such as *temperature inversion* whereby the temperature of the air increases with altitude can result in pollution particles being trapped in mist bands. Since the air close to the ground is cooler than the air above it, the process of convection is hampered [14], and harmful particles that are released into the air are thus unable to rise and will be deposited on the insulators. Areas that are prone to temperature inversion are Johannesburg and Witbank during winter, with Kwazulu-Natal and the Western Cape experiencing the same phenomena all year round.

4.4 PHASE TWO MAP

The phase two map (see Appendix B) was based on an electronic questionnaire survey. The questionnaire was developed using the Microsoft Access software database program. Principles and guidelines as prescribed by the IEC 60815 [3] were used in an algorithm to be able to determine the ***insulator pollution severity level*** (or the stress) that would be experienced in a particular area. The algorithm further identifies the ***existing insulation level*** (or strength) by assessing the in-service performance of insulators. The electronic insulator pollution questionnaire proved to be a very useful tool if correctly applied which could assist in the identification of atmospheric pollution sources, severity levels, and line insulation levels in a particular area. Therefore, a good understanding of the components mentioned is crucial for the successful use of the questionnaire.

The questionnaire was distributed to 200 Eskom technical service centres (TSCs) throughout South Africa. The questionnaire was completed by the TSC supervisor and sent back via Email - and all the data was fed into a central database for processing of the map. In instances where there was no response from the TSC a telephonic interview was conducted and the feedback fed into the central database.

The objective was to ascertain whether this method (questionnaire survey) could be used to develop an Insulator Pollution Severity Application Map (IPSAM). It should be mentioned at the outset: "To align ourselves with the primary objective, the map is presented directly as derived from the questionnaire feedback".

The information was reviewed and it was found that there is gross exaggeration of the contamination levels for most of the TSCs when compared to results from the phase one map. Further investigation revealed a ***lack of understanding by field personnel*** (the ones who completed the questionnaire) of the influence of environmental factors on insulator performance, which in turn ***resulted in the "unrealistic" and "exaggerated" pollution severity levels*** for certain TSCs. It was felt that this approach could only be pursued once field services personnel had sufficient training on insulator pollution and the impact on insulator performance. The lessons learnt and the shortcomings of this approach are highlighted in this section.

4.4.1 Questionnaire development

The electronic questionnaire was divided into five sections:

- An Introduction (an introduction and welcome note),
- TSC information (contact details, location, mail address),
- **pollution sources** (identify Marine, Industrial, and Agricultural),
- **In-service performance** of insulators (existing insulation levels for the TSA),
- Climatic factor (wetting) of each area (prevalence of rain, mist and fog), and
- Final pollution classification (for the TSA).

(1) Introduction

The user is introduced to the electronic questionnaire program, see figure 4.2.

(2) TSC information

Each of the 200 Technical Service Centres (TSC'S) had to update the information, see figure 4.3. A welcome note is displayed in figure 4.4.

(3) Pollution sources

Figure 4.5 show the electronic questionnaire display for pollution sources (marine) for one of the 200 technical service centres (TSC), this is also referred to as the stress that the insulation has to withstand. The software programme display for industrial and agricultural pollution looks the same.

Table 4.4 illustrates how the questionnaire assigns an area of impact for each pollution severity classification [1], [3].

Table 4.4: Questionnaire area of impact for pollution severity

Pollution source	Pollution severity	Pollution level	Minimum specific creepage distance (mm/kV)
1. Coastal / Marine	0 – 10km from coast	Very heavy	31
	11 – 20km from coast	Heavy	25
	21 – 50km from coast	Medium	20
	> 50km from coast	Light	16
2. Industrial	0 – 10km from coast	Very heavy	31
	11 – 20km from coast	Heavy	25
	21 – 50km from coast	Medium	20
	> 50km from coast	Light	16
3. Agricultural	≤ 20km form source	Medium	20
	> 20km from source	Light	16

(4) In-service performance of insulators

The existing insulation levels and the in-service insulator performance are determined as shown in figure 4.6.

The existing line specific creepage distance (S_{line}), or line insulation, for a specified system voltage (i.e. 66 or 132 kV) is calculated using the following equation [5], [10], [61]:

$$S_{line} = \frac{N \text{ x } 280}{1.1 \text{ x } V} \quad \text{(mm/kV)} \qquad (4.1)$$

where N : number of glass disks in the insulator string

V : system voltage

280 : refers to the creepage distance (in mm) for a standard cap and pin glass disk (U70BL)

The line insulation is then equated to a pollution classification indicating the ***insulation strength*** of the line (i.e. 23 mm/kV = CLASS II, or Medium).

4.4.1.1 Under-insulation

The questionnaire algorithm determines whether the line is under-insulated based on several factors as explained below:

- The insulator performance history (insulator flashover incidents) known at the time.
- ***Pin corrosion*** on a glass disk insulator is a key indication of the presence of high leakage current activity. If the line is prone to flashovers and the glass disk insulators experience pin corrosion, then a 'greater than' (>) sign is added to the line description of the line insulation classification (for example, > medium). This sign signifying that the creepage distance of the insulator string should be increased to cater for one pollution level higher (i.e. heavy = 25mm/kV or higher).
- The questionnaire algorithm ignores insulator flashovers that occurred as a result of lightning strikes.

(5) Climate Factor (wetting)

Figure 4.7 shows the questionnaire display for climate factor. The questionnaire algorithm incorporates the following equation for climate factor (C_f):

$$C_f = \sqrt{\frac{(F/20) + (D/3)}{2}} \tag{4.2}$$

where F : number of fog (mist) days experienced per annum

D : number of dry months (months with rain less than 20mm)

Once the climatic factor is calculated, the status of the wetting is made known:

- good wetting : climatic factor should be less than 1 (i.e. $C_f < 1$)
- critical wetting : climatic factor is greater than or equal to one (i.e. $C_f \geq 1$)

A high number of fog/mist days, with little rain, increase the occurrence of critical wetting [11]. In order to determine the degree of wetting in a particular area, a climatic factor is utilised. The climate factor is therefore an indication of dry-spells (continuous months with rain less than 20 mm) and wetting (continuous fog or mist days per annum).

The amount and type of wetting, directly impacts on the amount of pollution that is allowed to build up on an insulator surface [5], [12]. The way in which the pollution dissolves (or washes naturally), directly affects the insulator's performance. A good climatic factor is representative of an area with frequent, good wetting [11], [12].

(6) Final pollution Classification

Figure 4.8 illustrates how the questionnaire assigns the final pollution rating for a particular area (TSA).

The pollution classification for each pollution type (marine, industrial, agricultural) and the overall pollution classification (i.e. medium) is given.

The existing insulation level (line identification) is given and under-insulation is highlighted (i.e. > medium). The climate factor is also given (i.e. critical).

Finally, the questionnaire algorithm assigns the overall pollution classification the area or TSA (i.e. Very Heavy). The final pollution classification does not mean that the whole area is affected by the pollution severity (since this could be a localised problem), however, it highlights the highest pollution severity level that can be encountered in this area.

4.4.2 Electronic questionnaire flowchart

Figure 4.1 shows the questionnaire flowchart (see Appendix C for detail). The pollution sources can be interpreted as a stress and the field performance (or line insulation) as the strength of the network.

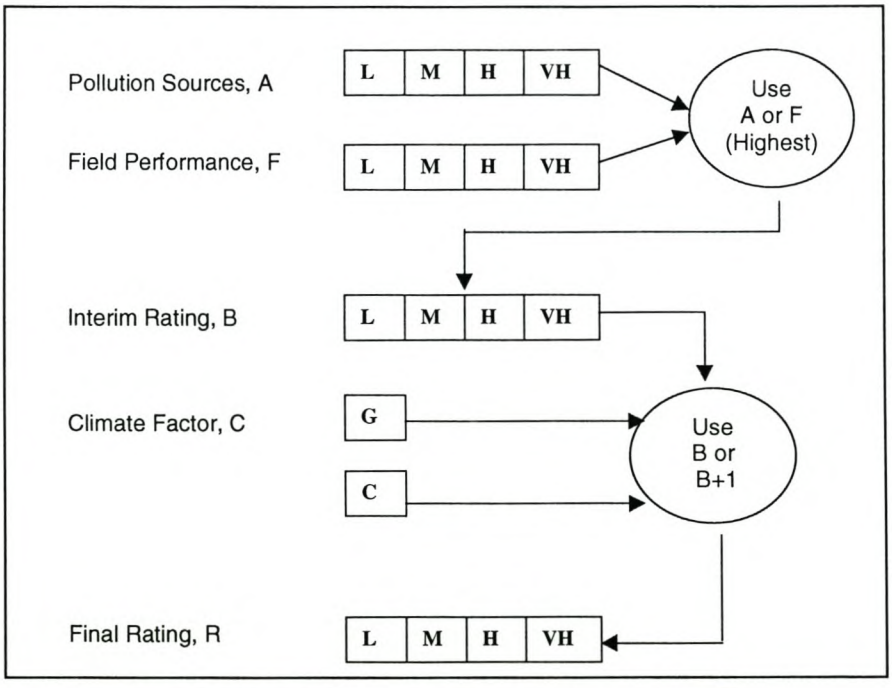

Figure 4.1 Questionnaire Flowchart

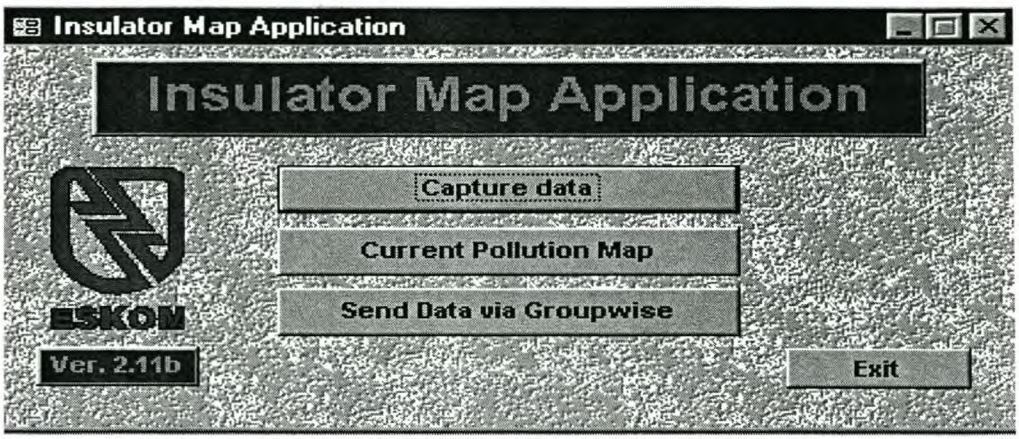

Figure 4.2 Questionnaire introduction

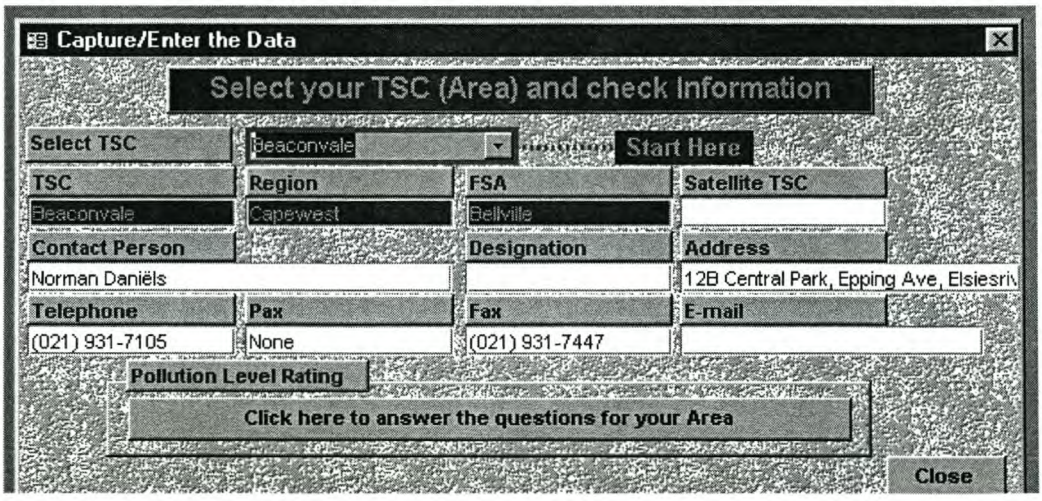

Figure 4.3 TSC contact details

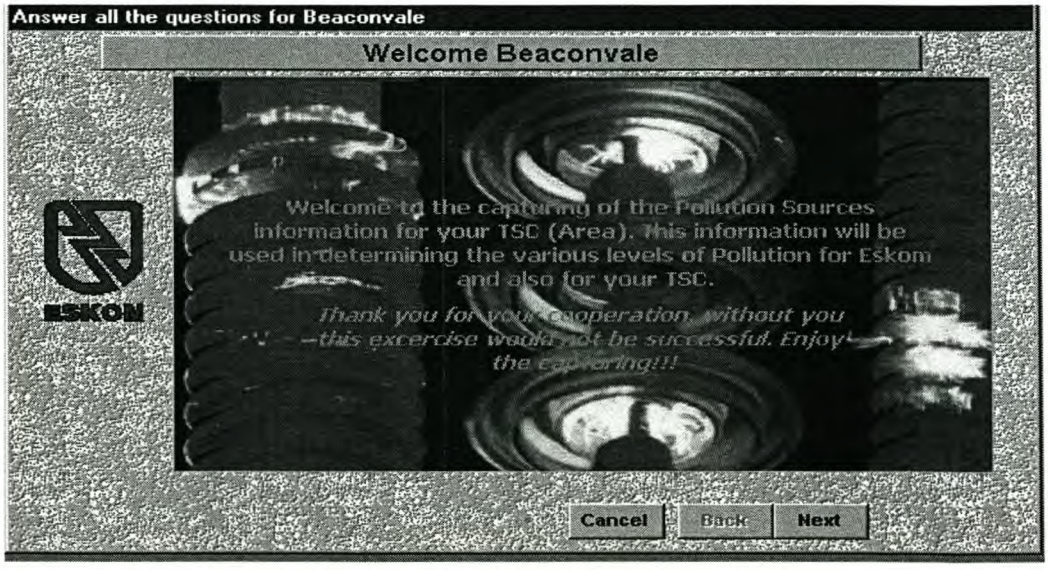

Figure 4.4 Welcome note

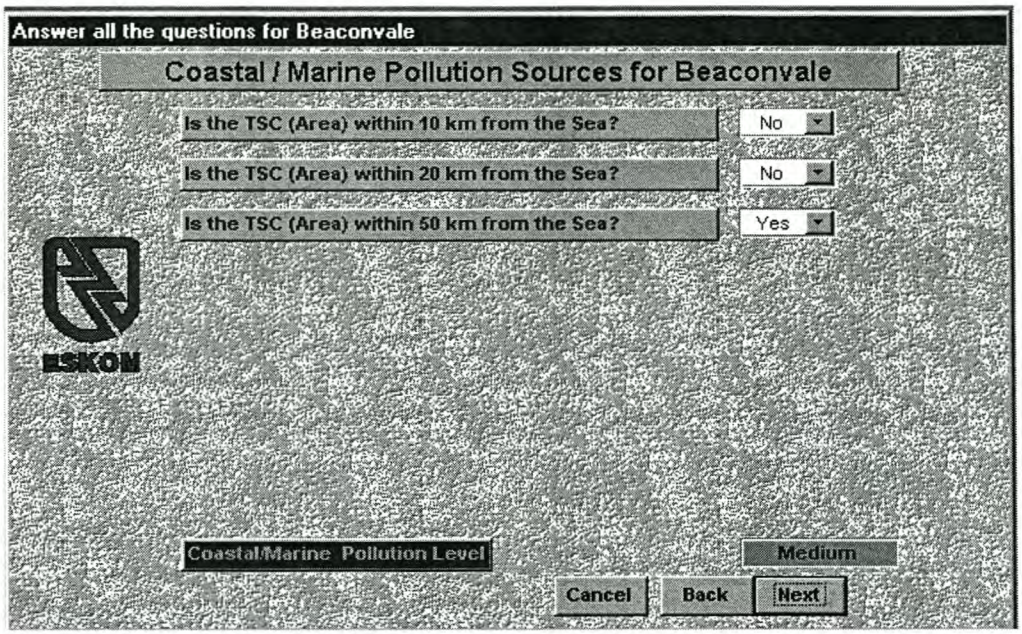

Figure 4.5 Marine pollution questions

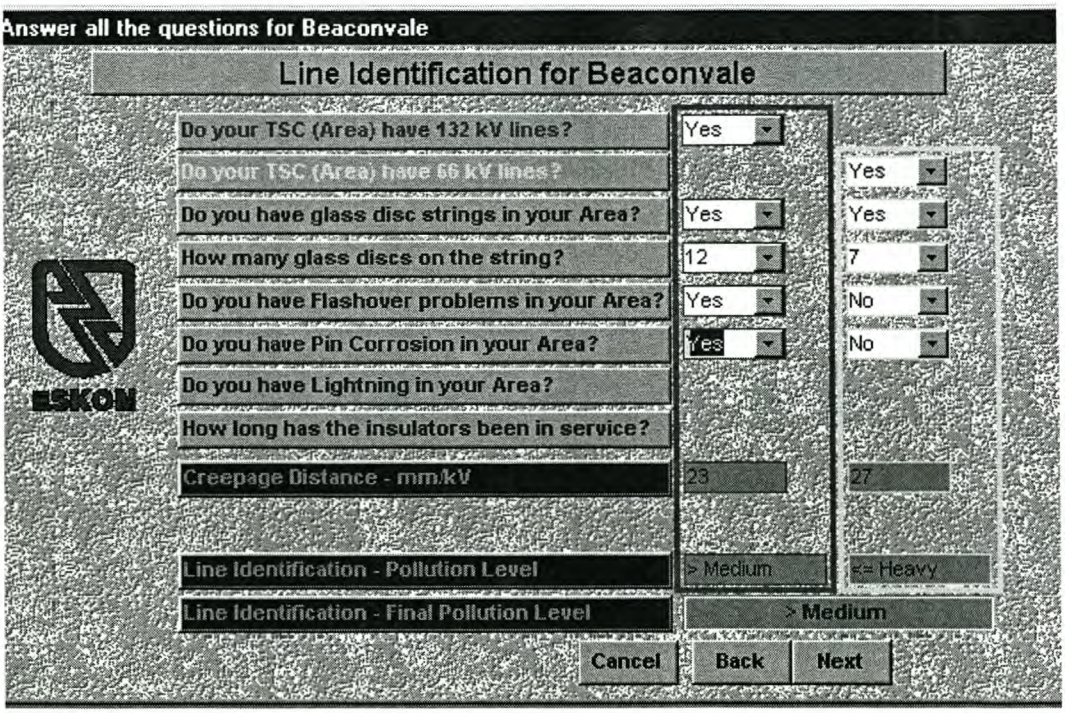

Figure 4.6 In-service assessment of insulators

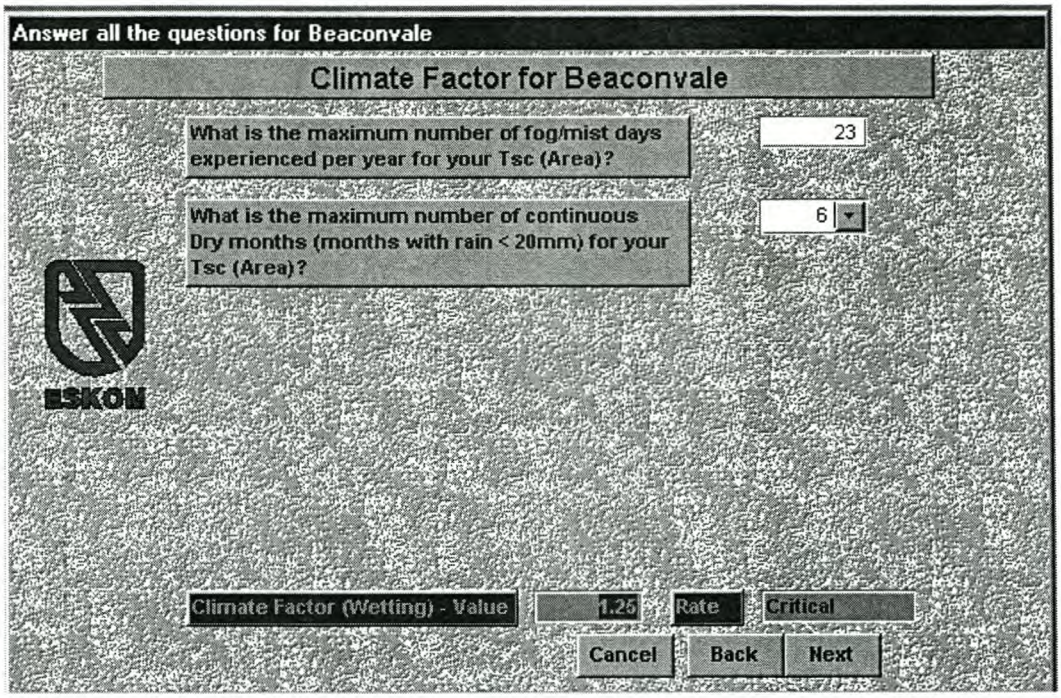

Figure 4.7 Climate factor

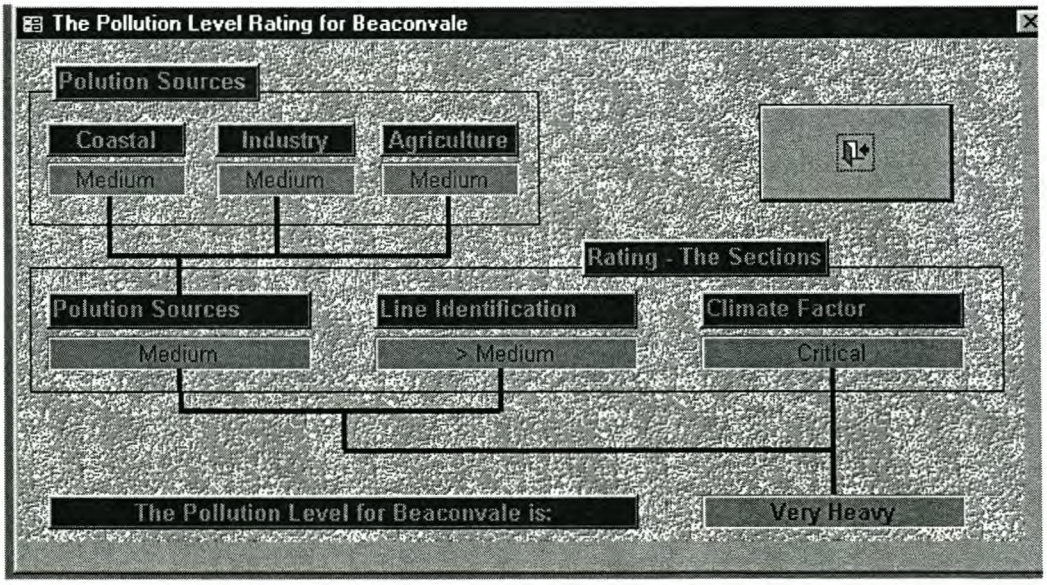

Figure 4.8 Final pollution classification

4.4.3 Phase two map results: Western Cape

Although 200 technical service areas (TSA's) from seven regions responded to the questionnaire, either by email or telephonically, only the Western Region's results are amplified in this section for further discussion.

A summary of the Western region's questionnaire data is given as follows:

1) 19 TSA's gave feedback via email and 3 via telephonic interview,
2) 17 TSA's (77%) have a very heavy pollution classification,
3) 3 TSA's (14%) are insulated for a very heavy pollution classification (>31 mm/kV),
4) 18 TSA's (82%) are insulated for a medium pollution classification.

The results are displayed in Table 4.5 and Figure 4.9. It is evident that the insulation level for 14 TSA's (or 63%) must be increased to cater for the very heavy pollution severity levels. However, this under-insulation could be very localised and should be authenticated with pollution measurements.

Table 4.5: Western Region's electronic questionnaire results

DESCRIPTION	RATING				
	L	M	H	VH	Total
POLLUTION (stress)	0	4	1	17	22
	0%	18%	5%	77%	100%
INSULATION (strength)	0	18	1	3	22
	0%	81%	5%	14%	100%

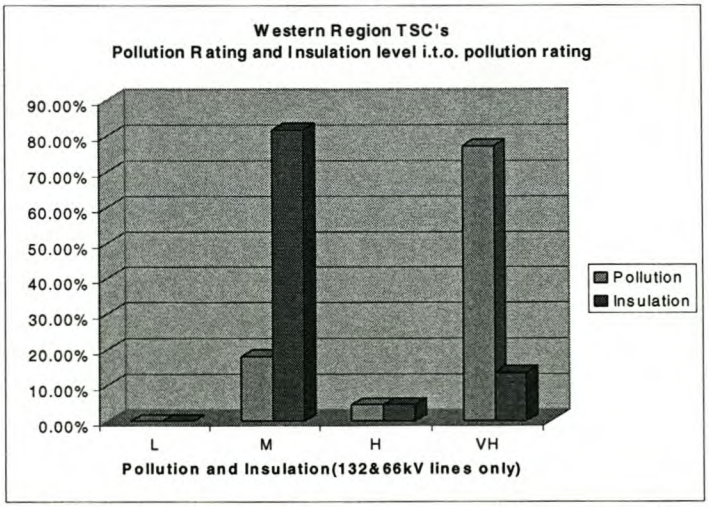

Figure 4.9 Summary of the Western Region's questionnaire data

4.5 LESSONS LEARNT: PHASE ONE AND TWO MAPS

Phase One Map

A few lessons can be learnt from the phase one development:

- The phase one approach provides a ***very general idea*** of the expected pollution levels and the areas affected.
- The areas of concern (i.e. with very heavy/heavy pollution levels) can be identified but is based on questionable factors (i.e. relating to geographical location: coastal, industrial, rural) rather than empirical data.
- No specific area of impact is empirically (without any doubt) identified for a particular pollution level but only generally defined. For example, the whole TSA is highlighted according to the highest pollution severity although this might only impact a small area.
- ***It is possible*** to develop an insulator pollution map based on a literature survey (i.e. the criteria covered in this section) however, as previously mentioned, it would be a ***very generalised representation***.
- Pollution measurements will verify the findings of a literature study.

Phase Two Map

A few lessons are noted from the phase two map development:

- A pollution severity map can be developed from a questionnaire; however, this is very reliant on the interpretation and knowledge of an individual.
- One of the greatest drawbacks is the fact that no, or very limited, empirical proof (or measurements) existed to verify any results.
- A large area, the complete TSA, is rated according to the highest pollution although the impact can be very localised. This does not help much if the exercise is looking at cost-saving measures in respect of area of impact. This is identified as one disadvantage since specific geographical pollution impact was not clearly defined.
- The electronic questionnaire proved to be a ***useful tool*** since it can be used to assess the pollution severity and insulation of a large area, or a single line, or a substation, or even just a piece of equipment (i.e. surge arrester, CVT, CT, bushing and line isolator) in a short period of time. However, a ***good understanding of atmospheric pollution sources, severity levels, and line insulation levels*** is crucial for the successful use of the questionnaire.

- The questionnaire must be completed on a computer since it is a software (electronic) based questionnaire. Field personnel did not always have access to a computer and the survey had to be done via telephonic interview.
- The field personnel did not always respond timeously and an alternative (telephonic interviews) had to be used.
- Telephonic interviews and verification checks revealed the field personnel's lack of understanding of environmental factors as an influence on insulator performance. Questionnaires were sometimes completed incorrectly.
- The best way to verify pollution levels is to introduce an extensive pollution measurement program.

4.6 SUMMARY: PHASE ONE AND TWO MAPS

The phase one and phase two Insulator Pollution Severity Application Map (IPSAM) for South Africa are shown in Appendix A and B respectively.

Phase One Map

The aim of the phase one map was to determine the highest pollution level in each technical service area (TSA) based on a literature review of pollution sources and their severity. The phase one map was predominantly based on a corrosion map but factors such as pollution sources, meteorology, topography, and previous insulator pollution measurements were included in the literature study.

The majority of the energy hubs reside in the very heavy and heavy pollution environment (25% of the country). Areas of concern are hubs such as Durban, Johannesburg, Cape Town, Port Elizabeth, Bloemfontein and Kimberly. Agricultural activity such as maize and sugar cane invariably display higher pollution levels due to *seasonal* crop spraying, harvesting and burning of crop residues.

Phase Two Map

The phase two map, on the other hand, was compiled using an electronic questionnaire that was completed by field personnel in each Eskom technical service area (TSA) within the RSA.

Comparison between phase one and two map developments

Table 4.6 is a comparison of pollution severity results for the phase one and two maps. The phase one revealed that approximately 10% of the country can be classified as having very heavy pollution, 15% as heavy, 70% in the medium class, and the remaining 5% as lightly polluted. The phase one map also correlate very well with the first nationwide dust gauge survey (Table 4.2) conducted by Macey [6].

The phase two map indicate that 55% (110 out of 200) technical service areas (TSA's) in the country experience very heavy pollution. This percentage also includes areas that are subjected to frequent critical wetting and/or have a poor line performance (insulator flashovers). It is also shown that 22% (44 out of 200) of the TSA's are situated in areas that have medium to light pollution levels. The ***results for the phase two map are unrealistic***, but as previously pointed out (section 4.4), this was ***based on human interpretation*** (field staff with a limited understanding of pollution and impact on insulator perfomance) and clearly shows the need for proper training and a pollution measurement programme.

Table 4.6: Pollution severity comparison for the phase one and two maps

Pollution Severity	**Phase One Map (%)**		**Phase Two Map (%)**		**Macey (1980) study (%)**	
Light	5	75	2	22	45.9	75.41
Medium	70		20		29.51	
Heavy	15	25	23	78	19.39	24.59
Very Heavy	10		55		8.2	

4.7 CONCLUDING REMARKS

Two preliminary insulator pollution severity application maps were developed. The basic reference document was the IEC 60815 guideline [3].

The phase one map was based on a literature study and is a generalised representation of insulator pollution severity levels.

The phase two map was developed using an electronic questionnaire survey that was completed by field service personnel. The phase two map was found to be "unrealistic" and there is "gross exaggeration" of the contamination levels for most of the TSCs when compared to results from the phase one map. This is firstly attributed to the effects of the Climate Factor that is greatly over-emphasised in the questionnaire algorithm (the weightings used for various parameters in the questionnaire algorithm require substantial revision). Secondly, the poor results are ascribed to the lack of understanding by field personnel of environmental pollution and the impact on insulator performance (showing the need for proper training and a pollution measurement programme).

The electronic insulator pollution questionnaire proved to be a very useful tool if correctly applied which could greatly assist in the identification of atmospheric pollution sources, severity levels, and line insulation levels; however the effectiveness of this tool is limited to a good understanding of insulator pollution and the impact on performance.

It should be noted that there is a vast difference between the phase one map and the phase two map. This is attributed to the methods that were used in developing the two maps, the phase one map was based on a literature survey and empirical studies, while the phase two map was based on human interpretation. The phase one map showed that 25% of the country is in the heavy to very heavy pollution severity, while the phase two map reflected a 78% for the same pollution criteria – exaggerated contamination levels in phase two, which if applied, could lead to costly over-insulation of lines and substations.

The major shortcoming in describing insulator pollution severity levels for South Africa using the phase one and two maps is the lack of proof by empirical (measured) data.

TEST SITE SELECTION

This chapter discusses the criteria to determine the selection of a test site for environmental pollution measurements. The methodology for setting up a test site for distance-to-coast pollution measurements along the Koeberg-Muldersvlei 400kV line is discussed in detail, and the environmental and climatic conditions prevalent in the proximity of this line are covered.

Another test site was identified for a height-above-ground level study. The selection criteria for this test site are also discussed.

5.1 SITE SELECTION

5.1.1 Criteria for site selection

In order to determine the location for monitoring stations, the following factors were considered [50], [51], [52], [21]:

- **Transect**: a primary aim is for transects to be as close to the direction of prevailing winds from the ocean (while still being approximately normal to the coastline).
- **Suitability**: the potential to locate suitable sites without sacrificing any other factors.
- **Topography**: the land topography especially that in the proximity to the ocean must be flat open ground. High mountains and hills act as barriers to the transportation of air-borne pollution.
- **Vegetation**: the land vegetation assists in early gravitational fall-out of pollution particles.
- **Security**: the test sites must be, as far as possible, inaccessible to the general public to prevent vandalism. Areas where houses and large buildings are situated must be avoided.

- **Accessibility**: monitoring sites must be visited on a monthly basis; this frequency requires easy access (close to roads).
- **Pollutants**: the type of pollution is seen as a primary factor for the location of a monitoring station.

5.1.2 Monitoring site selection: Koeberg-Muldersvlei 400kV line

The Koeberg-Muldersvlei 400 kV line was selected as the location for setting up the distance-to-coast monitoring stations. The reasons and advantages for the selection are discussed below:

- The Koeberg - Muldersvlei 400 kV line, starting at the Koeberg Nuclear Power Station (KNPS) progresses towards Muldersvlei 30 km from the coastline. This was ideal and monitoring stations were placed along the line.

- At the coast, some 40 metres away from the shoreline, there is an established insulator pollution monitoring site. The KIPTS (Koeberg Insulator Pollution and Test Station) station was used en as the coastal test station for the distance-to-coast study.

- The Koeberg - Muldersvlei 400 kV line passes an array of environments ranging from marine (in the west) and industrial (running on the outskirts of industrial areas with impact of air-borne pollution) to agricultural (90 % of the line - intensive farming - ploughing, fertilisers).

- The line servitude, starting at the Koeberg Nature Reserve (a prohibited area) passes through farmlands, is scarcely populated and limited to public access.

- The first few kilometres from the coast is fairly flat; up to 5 km from the coast the topography increase is small - up to 82 m above mean sea level (MSL), up to 10 km the increase is steady to 167 m and then declines to 159 m at Muldersvlei substation.

- The vegetation seldom reaches heights of more than 2 metres over the first 3 km from the coast, up to the 5 km point vegetation with heights of 3 to 5 metres or higher is not uncommon. The rest of the area up to 30 km from the coast (Muldersvlei substation)

can be considered as active farmlands with seasonal crops (wheat) growing up to 1m high.

- The location of the line, in the Cape Peninsula, also had additional financial benefits (reduction in cost, travelling time, etc.).

- Another great advantage was the location of the Koeberg Weather station, approximately 800m (to the east) of the shoreline and about 800m (to the south) of the Koeberg - Muldersvlei 400kV line. The meteorological data obtained from this weather station was used for correlation studies.

- The 120m high weather mast was used for height-above ground measurements (see chapter 7).

5.1.3 GPS map: Distance-to-coast monitoring

In order to conduct distance-to-coast pollution measurements, monitoring stations were set up along the Koeberg-Muldersvlei 400 kV line at intervals of 1 km up to 10 km from the coast, at 15-, 20-, and 30 kilometres from the coast (see figure 5.1).

One problem had to be overcome; the fact that the transmission line do not run perpendicular to the coastline. This was resolved by using GPS (geographic positioning system) technology. The GPS coordinate (geographic X-Y coordinate) for each monitoring station were determined from existing maps. Table 5.1 is a summary of the GPS coordinates for various monitoring stations at set intervals from the coastline. Appendix D shows how a GPS base station was set up.

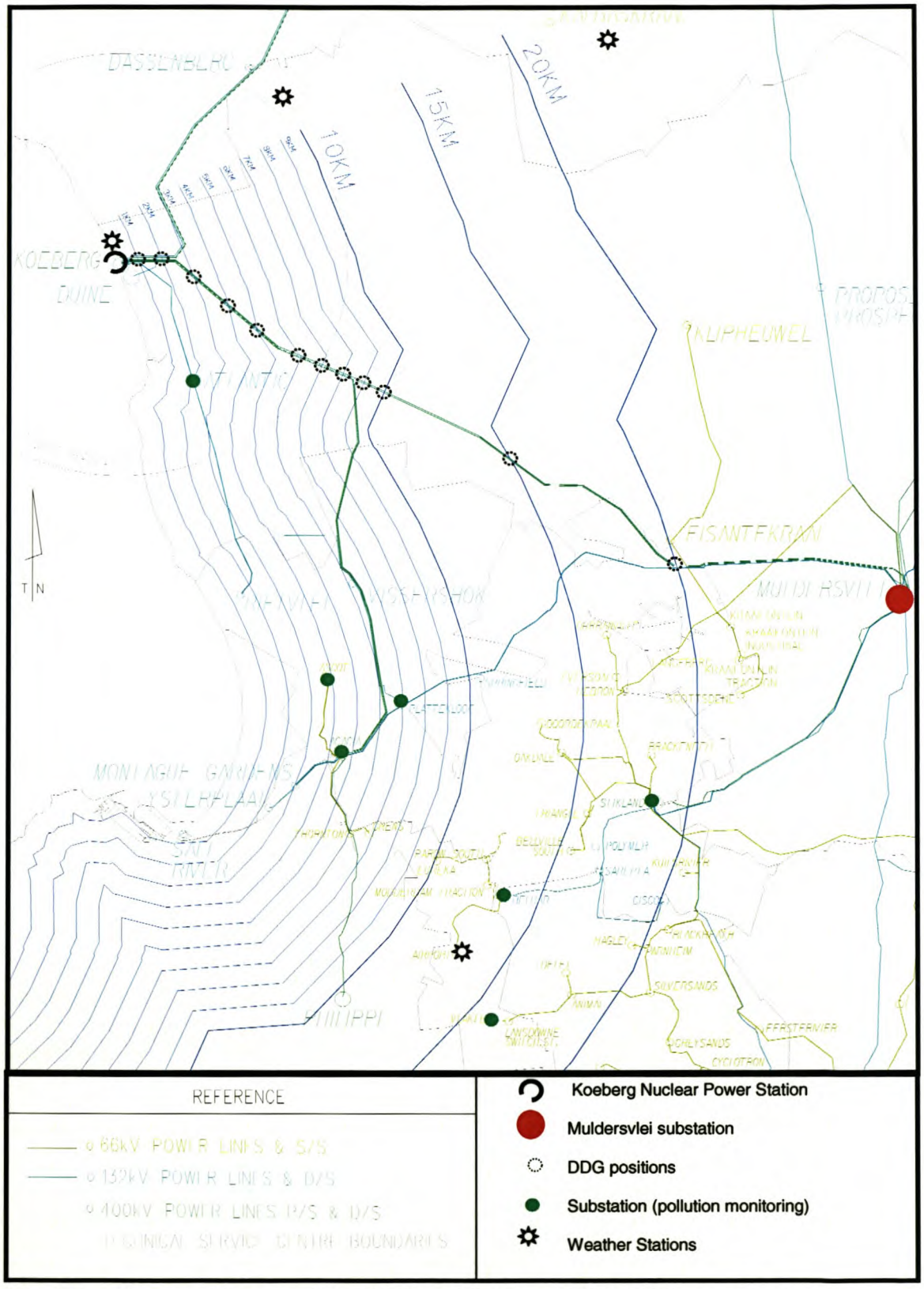

Fig. 5.1 Topographic map of the Koeberg-Muldersvei 400 kV line servitude and distance-to-coast pollution monitoring stations (DDG, ESDD and corrosion measurements)

Table 5.1: GPS coordinates for pollution monitoring stations

LO SYSTEM 19 DEGREES				
Distance from coast (km)	**WGS84**			
	Y	**X**	**Latitude**	**Longitude**
1	51568.783	3726948.209	33 40 04	18 26 38
2	50498.818	3726948.361	33 40 04	18 27 20
3	49172.611	3727622.162	33 40 26	18 28 11
4	47615.062	3729025.743	33 41 12	18 29 11
5	46327.177	3730186.306	33 41 50	18 30 01
6	44435.628	3731456.501	33 42 31	18 31 14
7	43433.936	3731897.846	33 42 46	18 31 53
8	42518.546	3732301.163	33 42 59	18 32 29
9	41607.745	3732715.64	33 43 13	18 33 04
10	40711.884	3733166.427	33 43 27	18 33 39
15	35146.497	3736341.899	33 45 11	18 37 14
20	27833.822	3741424.601	33 47 57	18 41 58

Project: Distance-to-coast pollution measurements

Location: Koeberg – Muldersvlei 400 kV line

NOTE:
The following monitoring sites are not listed above since they were existing stations:

1) KIPTS (50 m from shoreline)

2) Koeberg Weather Station (800 m from coastline)

3) Muldersvlei substation (30 km from coastline)

5.2 ENVIRONMENTAL SURVEY

Figure 5.2 is a topographical map showing the area that was selected for the atmospheric pollution monitoring study. The area starts at Koeberg on the west coast and progresses inland towards Muldersvlei in the south-east some 30 km from the coastline.

As previously mentioned, a primary objective of this research project was to determine aerosol migration progressively inland from the coast; this was accomplished using distance-to-coast pollution measurements. A literature review and site visits were performed to determine the environmental factors prevalent in the vicinity of the monitoring area. The results are summarized below.

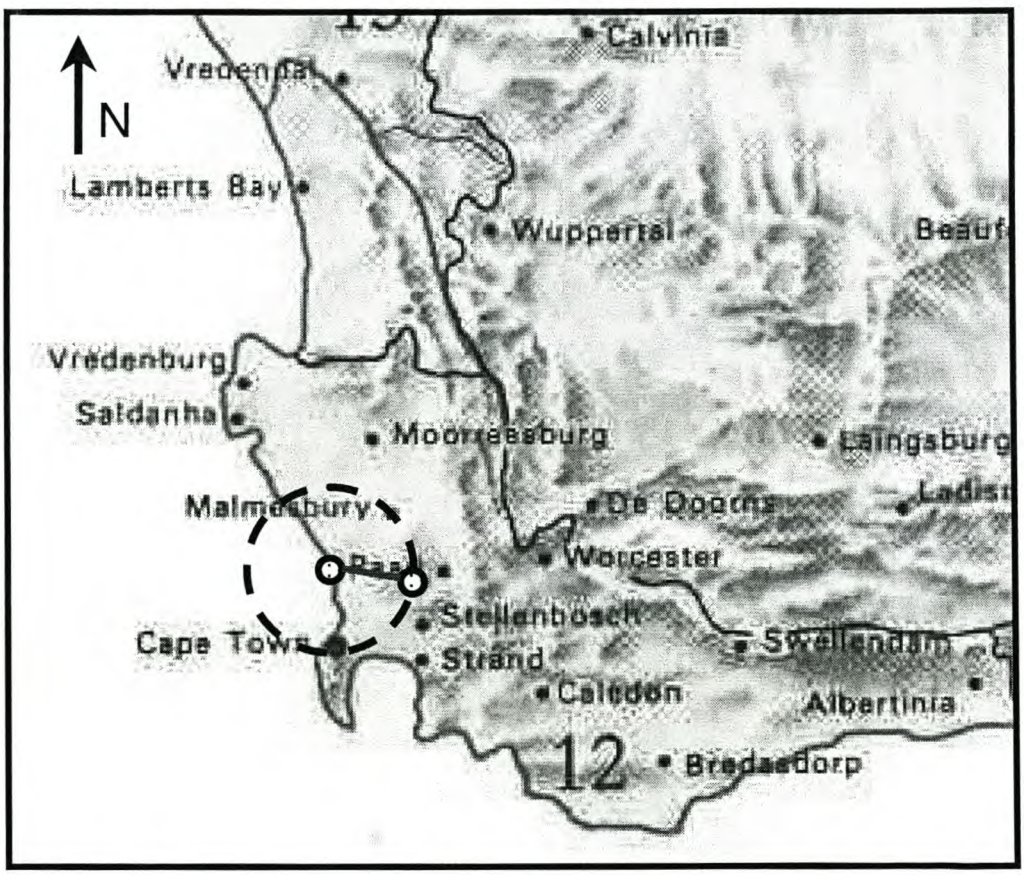

Fig. 5.2 Geographical map of the pollution monitoring area from Koeberg to Muldersvlei

Vosloo [21] performed a detailed investigation into the environmental factors in and around the KIPTS monitoring station. A summary of the main sources of atmospheric pollution in the vicinity of the monitoring area is:

- **Marine:** The Atlantic Ocean on the west; wave action, sea breezes (winds) and periodic mist banks are the cause for aerosol migration (moisture, salt particles, and plankton) from the coast moving inland.

- **Industrial:** The Atlantis industrial area (10 - 13 km away) emits burnt diesel, coal and heavy furnace oil (HFO) particles into the atmosphere. Caltex Oil Refineries and the Kynoch Fertiliser plant are the main causes of severe particle emissions.

- **Agricultural:** Agricultural activity (wheat, vineyards) results in occasional veld fires, ploughing, harvesting and crop spraying.

The literature review further revealed that Wicking-Baird *et al* [54] from the Energy Research Institute (ERI) at the University of Cape Town conducted a brown haze study for the Cape Town and surrounding areas over a one-year period from 1995 to 1997. Vosloo [21] also reviewed this study and refined some of the findings. The main sources of man-made pollution in and around the Koeberg area are summarised as follows:

- emissions from diesel and petrol vehicles (nitrogen oxide - NO_2),
- the burning of wood, coal and heavy furnace oil (HFO), and
- the Caltex Oil Refinery (sulphur dioxide - SO_2).

5.3 CLIMATIC CONDITIONS

It is imperative to have a good understanding of the climatic conditions prevalent in the vicinity of an atmospheric pollution station since this will enhance the understanding of measurement results and aid in correlation studies.

Chapter 2 covered, to some detail, the influence of climatic conditions on insulator pollution (section 2.1.5) and corrosion (section 2.2.4). Chapter 4 (section 4.3.6) discussed various climatic conditions that were investigated as part of the development of preliminary insulator pollution severity application maps (INSMAP).

Figure 5.3 is a graphical summary of the climatic regions in South Africa. A short review of the local climatic conditions prevalent in the proximity of the measurement area (Koeberg- Muldersvlei 400kV line) is given below.

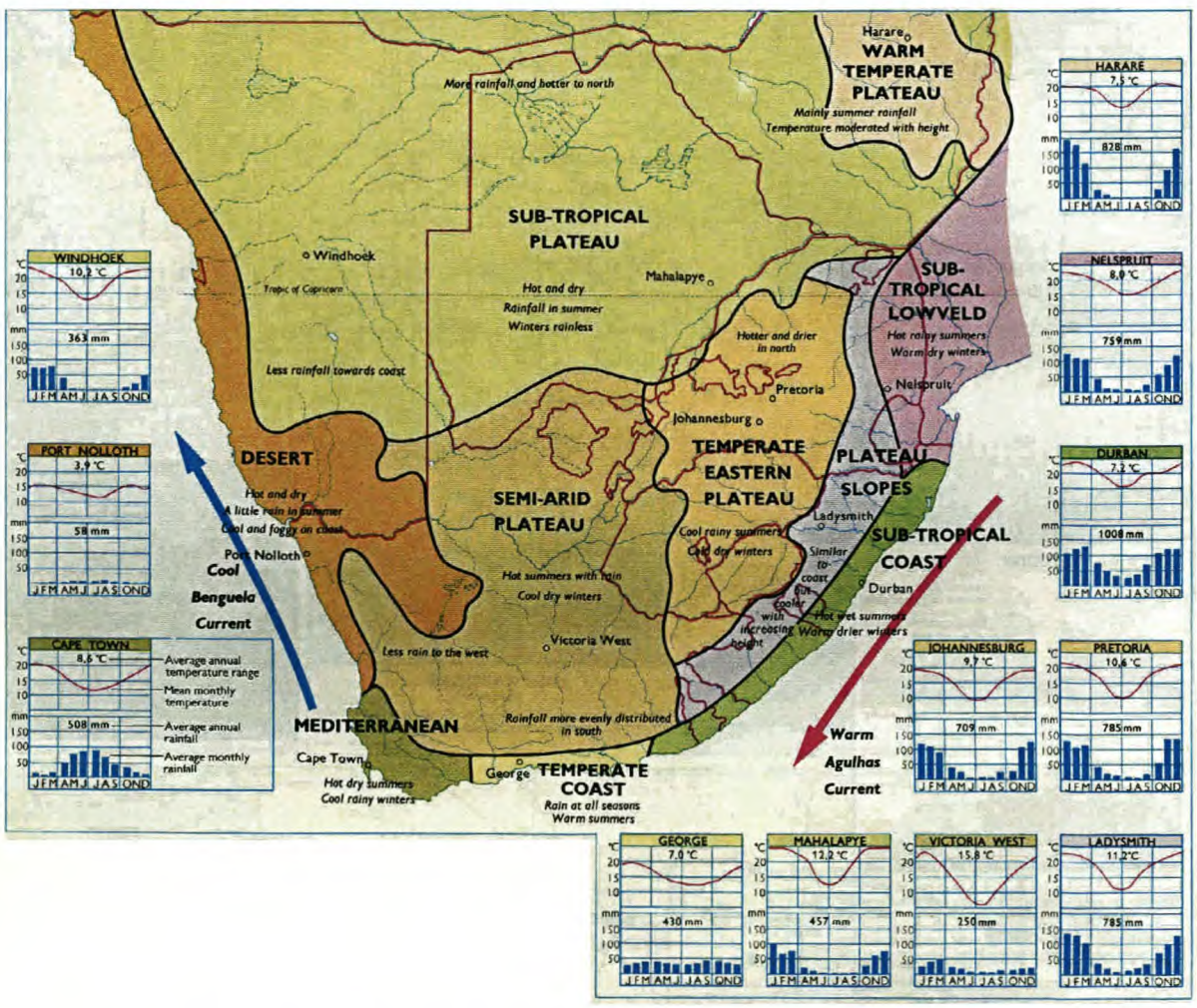

Fig. 5.3 Geographical map of Climatic Regions within South Africa

5.3.1 Climatic conditions: Koeberg-Muldersvlei 400kV line

The 30 km, Koeberg-Muldersvlei 400 kV line was chosen as the test area (as described in section 5.1). A short review of the local climatic conditions is provided below.

- **General description:** Koeberg is situated 20 km north of Cape Town, on the south-western tip of Africa, in the region generally known as the Western Cape, which is in the climate region of Southern Africa that is classified as Mediterranean Climate. The main feature of this climatic region is that the bulk of the rainfall occurs in winter. During the rainy months, April to September, approximately 320 millimetres of rain can be expected with as much as 15 rainy days per month. During the dry summer months however, only 3 to 5 rainy days occur, with the summer average rainfall of just more than 80 mm. Strong gusts of wind occur during the summer southerly associated with the ridging of a high-pressure system from the Atlantic to the Indian Ocean. In winter, frontal weather causes strong winds, hence the well-known name Cape of Storms. Gusts in excess of 35 metres per second have been recorded on numerous occasions. With the cloudy winters and sunny summers a total reversal of the so-called radiation climate is observed versus the summer rainfall regions [21].

- **Rainfall:** The rainfall of the Mediterranea-type climate district, in which Koeberg is situated, has a very low seasonal variability of below 20% [21]. The average annual rainfall equals 508 mm, with the highest (on average) monthly rainfall normally recorded in July (80 mm) and the lowest in December (5 mm) [7]. The statistical expectancy of precipitation intensity show that the maximum rainfall in a 60-minute period will not exceed 30 mm for a 20-year return period and 40 mm for a 100-year return period [21].

- **Fog:** The West Coast is liable to have a considerable amount of fog due to the cooling of moist air over the Benguela current. Sometimes the fog forms at sea then drifts inland on a light north-westerly breeze. If the ground is cold the fog persists, it lifts after sunrise and disperses an hour or two later. The approach of a depression causes a pressure gradient from the interior plateau to the coast. The air blowing over the coast is warm, and steep inversions form, which encourage the formation of fog. Inversion fogs or frontal fogs form when precipitation, especially drizzle, is evaporated into stable air cooled by contact with

the surface of the ground beneath. Generally, the month with the most fog is April and the one with the least is July. The foggy season usually starts in late summer to early winter, but there is no month free from fog [21].

- **Ambient temperature:** Situated on the Atlantic Coast, temperature variations are moderated especially when the wind is onshore. Microclimatological effects however, influence the temperature variations to such a degree that daily fluctuations exceeding 20 degrees Celsius are commonly observed. During subsistence conditions with a high pressure system being centralised over the area, clear skies and terrestrial radiation can cause the temperature to drop to close to freezing point. Daytime radiation results in a rapid rise in temperature that exceeds 20 degrees Celsius [21]. The average annual temperature range equals 8.6 degrees Celsius, the highest (mean) monthly temperature (21 °C) is recorded in January and the lowest in July (12 °C) [7].

- **Wind:** "Airflow is a direct result of pressure differences. As the Cape area is influenced by the strong pressure gradients of the mid-latitudes, the wind energy exceeds most other areas in Southern Africa. The ridging anticyclone situated over the south Atlantic in summer, with strong pressure gradients, results in strong southerly flow over the Cape Peninsula during the summer months. Contrasting with this, the winter northerly flow is caused by pre-frontal conditions that are also associated with cloudy weather and low temperatures. The southerly flow experienced after the passage of the frontal system has less strength than the summer southerly. On the Atlantic coast, where Koeberg is situated, a south-westerly sea breeze results when significant solar heating of the interior occurs. This condition starts during mid-morning and lasts until late afternoon. Drainage conditions are evident during night-time cooling of the higher interior or when a high-pressure system over the interior causes easterly berg winds [21].

Dispersion: To understand the dispersion potential, knowledge of the mid-latitude and major weather systems such as South Atlantic anticyclones and frontal systems are required. In winter, when frequent frontal systems pass over the Cape Peninsula, strong northerly to westerly winds occur 34% of the time. When upper air high-pressure systems occur inland, drainage conditions exist along the coast, which results in poor ventilation with a subsequent decline in dispersion potential. The depth of the nocturnal inversion layer, limiting dispersion, was found to be in the region of 300m. The terrestrial radiation at night, occurring frequently with relative calm wind conditions and clear skies at night in early winter, causes strong inversion conditions, resulting in a virtual impermeable layer restricting dispersion below 300m. In summer however, strong pressure gradients with the advent of the ridging South Atlantic anticyclone, cause strong southerly winds, which have excellent dispersion potential. These winds occur 39% of the time [21].

- **Variability of the Cape weather:** Due to topographical influences, enhanced by the two oceans bordering the Cape Peninsula, the spatial variability of the weather is indicated by rainfall differences. These statistical differences exceed a factor of four within a 400 square kilometre area. Yearly rainfall totals vary from just over 300 mm on the West Coast to long-term averages exceeding 1200 mm in mountainous terrain within 40 km between stations. This same variability is evident when comparisons are made from one year to another. Over a 20-year period, the maximum rainfall in one year exceeded 640 mm and the lowest rainfall recorded was less than 245 mm. Short-term variability is also evident in the weather that can be experienced over a very short period. A typical example of this variability is when a high-pressure system over the interior causes land breezes commonly known as 'bergwinds' - the winds originate in the east and heats up as it descends down the escarpment at a speed of approximately 20 km/h. This is a condition when even in the winter months the surface temperature will exceed 30 degrees Centigrade. This typical pre-frontal condition normally lasts one day and then a cold front, with gale force north-westerly conditions and a dramatic temperature drop down to below 15 degrees, occurs [21].

5.4 SUMMARY

The Koeberg-Muldersvlei 400 kV line was selected as the test site for the direct distance-to-coast atmospheric pollution regression study. A summary of the reasons for this selection is given below:

- The KIPTS site was identified as the most severe insulator pollution test-site in the world [21].

- Meteorological data is available from the Koeberg Meterorological Station for correlation studies.

- The vast array of environmental pollution conditions (marine, industrial and agricultural) along the 30 km Koeberg-Muldersvlei 400 kV line makes this an ideal test location.

- The climatic conditions range from hot dry summers to cool rainy winters providing a good spread of seasonal variation for analysis and correlation.

- The dominant wind direction during winter is north-easterly, and south-westerly in summer. The wind speeds can be extremely high (gale force). Westerly winds bring marine pollution, south-easterly winds bring industrial pollution, north-easterly winds bring rain, and easterly winds tend to be hot [21].

- The high humidity levels along the coast (75% during the day and 95% at night) [21].

  Correlation studies by Vosloo showed that in general the relative humidity had a large effect on leakage current activity on the insulator surface [21].

  Corrosion measurements form part of the study, and the humidity levels along the coast is an ideal condition for corrosion testing (accelerates corrosion rate). As stated by Stern *et al* [14] "*Moisture is critical to corrosion. Below 60% relative humidity corrosion is slow; at 80% there is a marked increase in corrosion; above 80% corrosion is very high; and finally corrosion is minimal during periods of rain (100%).*"

- Height-above-ground measurements, another primary objective of this study, could be carried out on the 120 m high weather mast located at the Koeberg Weather Station. Correlations between weather data and pollution measurement results were made possible since pollution monitors were installed at the same where weather data was recorded (see chapter 7 for more detail).

5.5 CONCLUDING REMARKS

Chapter 5 deals with the criteria that determine the selection of a test site for atmospheric pollution monitoring.

Based on the selection criteria specified, the Koeberg-Muldersvlei 400kV line was selected for a detailed distance-to-coast atmospheric pollution regression study (see chapter 6). A GPS map was developed to determine the geographical coordinates for each test site along the line.

The 120m high weather mast located at the Koeberg Weather station was selected for the height-above-ground environmental pollution study (see chapter 7) and the selection criteria was discussed.

6

DISTANCE-TO-COAST MONITORING

A distance-to-coast study was conducted along the Koeberg-Muldersvlei 400 kV line in the Western Cape. Two types of atmospheric pollution monitoring were utilised in this study: direct insulator pollution measurements (DDG and ESDD) and corrosion exposure tests (CLIMAT and flat metal specimens). The results are discussed in this chapter.

In order to determine the influence of distance from the sea on insulator pollution severity levels, the results obtained from test sites along the Koeberg–Muldersvlei line are discussed in conjunction with results from test sites at various locations in the Cape Peninsula, and along the West Coast and South Coast.

6.1 INSULATOR POLLUTION MEASUREMENTS

Two direct insulator pollution measurement techniques were used, DDG and ESDD (the test methodologies were discussed in chapter 3, section 3.1.1 and 3.1.2).

A summary of the dust deposit pollution index (DDG) and surface deposit index (ESDD) as derived by Vosloo [11] is given in Table 6.1.

Table 6.1: DDG and ESDD pollution severity classification indices

Severity Class		DDG pollution index		ESDD
		µS/cm		mg/cm^2
		monthly average	monthly maximum	monthly maximum
Light	**I**	0 to 75	0 to 175	< 0.06
Medium	**II**	76 to 200	176 to 500	0.06 – 0.12
Heavy	**III**	201 to 350	501 to 850	> 0.12 - 0.24
Very Heavy	**IV**	> 350	> 850	> 0.24

6.1.1 DDG measurements: Koeberg-Muldersvlei line

Monitoring stations for the direct distance-to-coast study were set up along the Koeberg-Muldersvlei 400 kV line (as described in chapter 5) covering a distance of up to 30 km inland from the coast. The measurements were carried out over a two-year period, starting in August 2001 and running to October 2003.

Figure 6.1 is a graph showing the effect of distance from the sea in relation to DDG conductivity values along the Koeberg-Muldersvlei 400 kV line. The DDG pollution levels can be classified as very heavy (or exceptional) for areas closest to the coast, within 1 km, with a steep decline moving inland.

Table 6.2 is a summary of the distance-to-coast DDG conductivity values. Detail monitoring results are provided in Appendix E.

NOTE: It was mentioned that the volume conductivity of the distilled water used for the measurements should not exceed 5 µS/cm (chapter 3, section3.1.1). However, due to limited availability of distilled water the volume conductivity exceeded 5 µS/cm in many instances (see Appendix E). This resulted in a measurement with a lower average conductivity value for the four directions.

It was mentioned that the maximum exposure period should not be more than 40 days (chapter 3, section3.1.1). However, the results for certain stations reflect the first measurements ttaken after a month, and in certain cases several days lapsed (161 and 206 days) before the next measurement were taken (see Appendix E). This long lapse is ascribed to the fact that some of the monitoring stations were set up – and measurements were taken for the first month - while other monitoring stations were not yet set up; ***the approach was to have all the stations set up and to resume measurements****. All the conductivity measurements are reflected in the tables and the graphs – for the longer exposure periods the conductivity measurement smooths out monthly (seasonal) changes and reflect the cumulative pollution.*

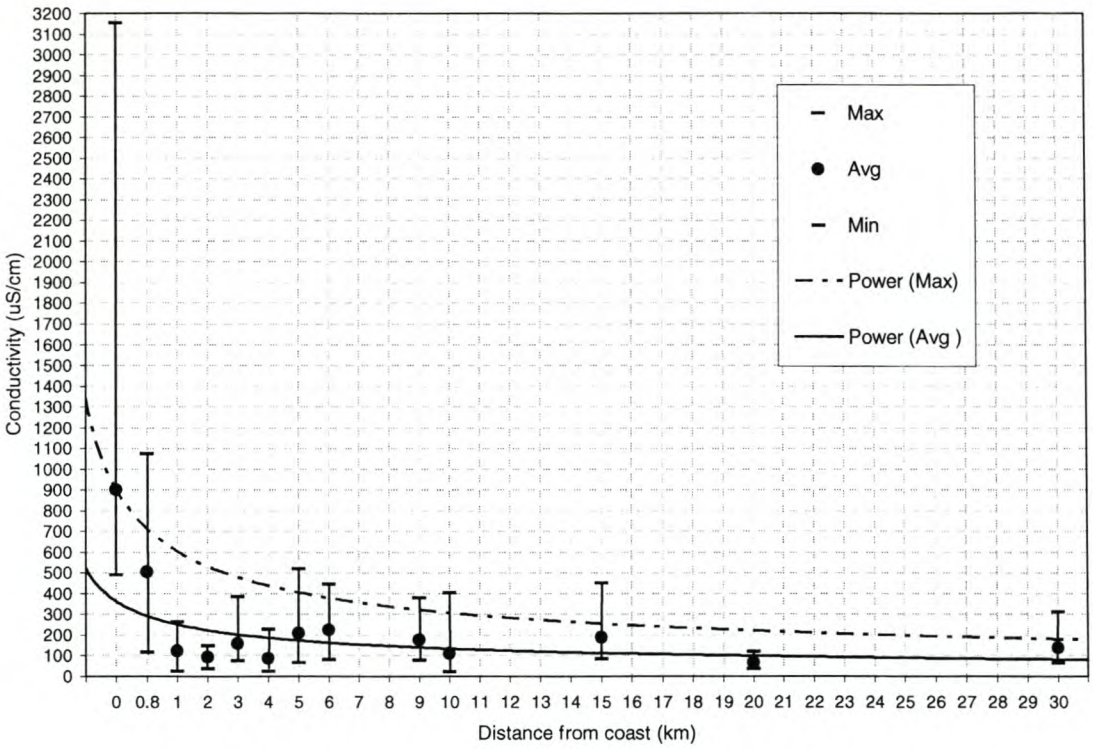

Fig. 6.1 Graph showing DDG conductivity values for distance-to-coast along the Koeberg-Muldersvlei 400kV line (Aug'01 to Oct'03)

Table 6.2: Distance-to-coast DDG measurement results along the Koeberg-Muldersvlei 400kV line.

Distance from coast (km)	Height above sea level (m)	DDG Conductivity (µS/cm)		
		Min	Max	Avg
0.05 (KIPTS)	1	489.5	**3153.5**	**900.88**
		Heavy	**Very Heavy**	**Very Heavy**
0.8 (WS)	5	117.29	**1073.5**	**503.07**
		Light	**Very Heavy**	**Very Heavy**
1 km	21	23.33	261.68	121.82
		Light	Medium	Medium
2 km	28	34.66	145.28	93.0
		Light	Light	Medium
3 km	29	74.63	383.33	157.85
		Light	Medium	Medium
4 km	29	24.75	226.28	87.84
		Light	Medium	Medium
5 km	82	65.73	519.64	**207.28**
		Light	Heavy	**Heavy**
6 km	122	79.34	444.92	**224.98**
		Light	Medium	**Heavy**
9 km	150	77.03	379.44	174.6014
		Light	Medium	Medium
10 km	175	22.27632	401.39	108.9303
		Light	Medium	Medium
15 km	51	83.1	449.86	188.68
		Light	Medium	Medium
20 km	139	34.76	120.44	65.07
		Light	Light	Light
30 km	159	63.42	309.25	135.82
		Light	Medium	Medium

Table 6.3: Direct Insulator Pollution measurements at various monitoring stations in the Cape Peninsula

Site	Distance from coast	ESDD (mg/cm²)					DDG (µS/cm)				
	(km)	From	To	Min	Max	Avg	From	To	Min	Max	Avg
KIPTS	**0.04**	1999	2001	0.016	0.212	0.111	1999	2001	489.5	**3153.5**	**1237.25**
				Light	Heavy	Medium			Medium	**Very Heavy**	**Very Heavy**
Atlantic	**0.5**	Mar'00	Nov'03	0.021	0.177	0.055	Mar'00	Nov'03	76.721	533.528	268.859
				Light	Heavy	Light			Light	Heavy	Heavy
Duine	**0.8**	Mar'00	Nov'03	0.022	**0.268**	0.069	Jun'00	Nov'03	208.705	**1562.146**	**591.207**
				Light	**Very Heavy**	Medium			Medium	**Very heavy**	**Very Heavy**
Khayelitsha	**1.5**	Mar'00	Nov'03	0.0145	0.1597	0.0462	Aug'00	Nov'03	126.161	**1246.23**	**451.168**
				Light	Heavy	Light			Light	**Very Heavy**	**Very Heavy**
Mpilo	**5**	Mar'00	Nov'03	0.0164	0.1942	0.056	Oct'00	Nov'03	149.732	**1093.8214**	**408.28076**
				Light	Heavy	Light			Light	**Very Heavy**	**Very Heavy**
Ascot	**7**	Mar'00	Nov'03	0.0113	0.1033	0.0334	Mar'00	Nov'03	137.676	598.956	286.242
				Light	Medium	Light			Light	Heavy	Heavy
Bluedowns	**8**	Mar'00	Nov'03	0.0088	0.1269	0.0273	Mar'00	Nov'03	48.546	367.357	135.170
				Light	Heavy	Light			Light	Medium	Medium
Plattekloof	**8**	Mar'00	Nov'03	0.006441	0.057078	0.0220808	Aug'00	Nov'03	69.5625	479.12069	202.29766
				Very Light	Light	Light			Light	Medium	Heavy
Vlakte	**9**	Aug'00	Nov'03	0.008379	0.080075	0.0375725	Aug'00	Nov'03	83.071429	513.83103	238.95879
				Very Light	Medium	Light			Light	Heavy	Heavy
Belhar	**10**	Mar'00	Nov'03	0.0124	0.0905	0.0314	Mar'00	Nov'03	72.078	327.61	152.366
				Light	Medium	Light			Light	Medium	Heavy
Acacia	**17**	Apr'00	Nov'03	0.0163	0.216943	0.05131	Apr'00	Nov'03	129.931	499.182	268.653
				Light	Heavy	Light			Light	Medium	Heavy
Stikland	**18**	Mar'00	Nov'03	0.010121	0.136634	0.0302256	Aug'00	Nov'03	54.085714	366.21892	153.62418
				Light	Heavy	Light			Light	Medium	Medium
Muldersvlei	**30**	Mar'00	Nov'03	0.003281	0.057286	0.0207549	Jun'00	Nov'03	30.198529	309.25459	116.88964
				Very Light	Light	Light			Light	Medium	Medium
Average				0.01284	0.14458	0.04548			128.92	**850.058**	346.99
				Very Light	Heavy	Light			Light	**Very Heavy**	Heavy

6.1.2 Pollution measurements: Western Cape

In the previous section, the focus was primarily on the Koeberg-Muldersvlei 400 kV line and the effect of distance-to-coast on insulator pollution severity levels along this line. The investigation was taken a step further by analysing test results (DDG and ESDD) from various monitoring stations within the Cape Peninsula, the West Coast, and the South Coast. Figure 6.2 indicates a geographical spread of the monitoring areas.

Fig. 6.2 Map of South Africa showing location of insulator pollution monitoring areas along the West and South coast

Table 6.3 is a summary of insulator pollution measurement results obtained from monitoring stations in the Cape Peninsula for a distance of up to 30 km from the coast. Table 6.4 is a summary of pollution measurement results taken along the West and South Coast. The measurements were taken over a period of three years, from March 2000 to November 2003. The following discussion will highlight some of the findings.

Table 6.4: Insulator pollution measurements along the West and South coast

Insulator Pollution Measurements								
Region	**Site**	**Distance from Coast**	**DDG (uS/cm)**			**ESDD (mg/cm2)**		
		(km)	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**
West Coast	**Brand Bay**	**3.5**	48.486	305.138	108.921	0.003	0.060	0.021
			Light	Medium	Medium	Light	Medium	Light
	Blouwater	**16.8**	28.795	541.374	190.512			
			Light	Heavy	Medium			
	Aurora	**21**	33.510	300.150	103.344	0.006	0.094	0.030
			Light	Medium	Medium	Light	Medium	Light
	Koekenaap	**28**	15.830	183.161	73.258			
			Light	Medium	Light			
	Juno	**31.5**	9.531	148.556	56.604			
			Light	Light	Light			
	De Hoek	**91**	42.350	300.893	156.793	0.010	0.163	0.045
			Light	Medium	Medium	Light	Heavy	Light
	Average		**29.750**	**296.545**	**114.905**	**0.006**	**0.106**	**0.032**
			Light	**Medium**	**Medium**	**Light**	**Medium**	**Light**
South Coast	**Proteus**	**17.5**	29.136	560.785	220.887			
			Light	Heavy	Heavy			
	Swellendam	**56**	92.377	787.863	**368.368**			
			Light	Heavy	**Very Heavy**			
	Bacchus	**98**	0.769	102.560	48.272			
			Light	Light	Light			
	Droerivier	**191**	6.567	37.734	17.555			
			Light	Light	Light			
	Average		**3.668**	**70.147**	**32.914**			
			Light	**Light**	**Medium**			

6.1.2.1 DDG measurements: Western Cape

Figures 6.3 and 6.4 illustrate average and maximum DDG conductivity test results respectively in relation to distance from the sea for monitoring stations along the Koeberg-Muldersvlei line (Table 6.2), the Cape Peninsula (Table 6.3), and along the West and South coasts (Table 6.4).

The plots are very similar in profile, the first few hundred metres from the coast are exceptional (very heavy) and a rapid decay is noted after about 1 km (10^3 m) from the coast. This is attributed to the gravitational fall-out of the larger pollution particles over the first kilometre from the coast.

Koeberg-Muldersvlei 400 kV line (Table 6.2)

Vegetation (plants and trees) growing as high as 5 m above ground level are densely populated between the 1 km to 4 km zone along the Koeberg-Muldersvlei line. This vegetation acts as shield, and prevents the migration and fall-out of smaller pollution particles within this zone, resulting in lower conductivity values. Pollution particles carried by on-shore winds will fall-out beyond 4 km from the coast – as noticed by the higher conductivity values at the 5 and 6 km monitoring stations.

Cape Peninsula (Table 6.3)

The maximum DDG conductivity values range between very heavy (up to 2 km), heavy (up to 9 km), and medium (up to 22 km) pollution categories. For average values the pollution classification vary from very heavy (up to 3 km), heavy (up to 9 km), to medium (up to 21 km).

West and South Coast (Table 6.4)

Along the West Coast, one station (17 km from the coast) recorded a maximum DDG conductivity value in the heavy pollution class, while three stations (3.5, 21, 28 km) recorded medium pollution and one station (31 km) recorded medium pollution levels. The average values ranged between medium (up to 21 km) and light pollution levels.

For the South Coast the maximum and average DDG conductivity values within 30 km from the coast are in the heavy category (17 km from the coast).

Attention is drawn to the Swellendam test site, located 56 km from the sea, where the highest monthly maximum DDG conductivity value was recorded (787.8 µS/cm) resulting in a heavy pollution severity classification. The highest monthly average DDG pollution value was also recorded at this site (368.36 µS/cm) resulting in a very heavy pollution severity classification. This is most probably attributed to localised industrial pollution.

6.1.2.2 ESDD measurements: Western Cape

Figures 6.5 and 6.6 illustrate average and maximum ESDD test results respectively in relation to distance from the sea for monitoring stations in the Cape Peninsula (Table 6.3), and along the West and South coasts (Table 6.4).

The plots are very similar in profile; stations within the first few hundred metres from the coast are 2 to 3 times higher than stations after about 1 km (10^3 m) from the coast. For average ESDD conductivity values (see figure 6.5) all monitoring stations up to 1 km from the coast recorded medium pollution severity levels, thereafter, moving inland the pollution severity remained in the light category. The maximum ESDD values produced very heavy pollution severity levels up to 1 km from the coast and heavy pollution severity as far as 22 km inland.

Cape Peninsula (Table 6.3)

The maximum DDG conductivity values range between light and very heavy; while the average values vary from light to medium.

West Coast (Table 6.4)

Along the West Coast the maximum ESDD conductivity values are within the medium and heavy category, while all the average values are in the light pollution severity level.

6.1.2.3 Variance between DDG and ESDD measurements: Western Cape

There is a noticeable difference between the results obtained with the DDG and ESDD techniques; for example, for average values the DDG values vary between very heavy and light whereas ESDD values only range from medium to light pollution severity (see figure 6.3 and 6.5).

This is ascribed to the method itself. The DDG technique reflects a cumulative contamination value, which also includes a maximum event. The ESDD technique, on the other hand, is a snapshot taken at that instant, this means that a maximum event could have been missed – maybe due to natural washing the previous day.

Each technique is useful and the need for either or both should be borne in mind when investigating an insulator pollution monitoring technique to be used.

6.1.3 DDG Probability plot: Koeberg-Muldersvlei line

Figure 6.7 shows the DDG average conductivity (μS/cm) probability plot in relation to the distance from the sea for 30 km inland along the Koeberg-Muldersvlei 400kV line.

From the probability plot it can be seen that there is a 50% probability that the maximum conductivity will be higher than 450 μS/cm over the 30 km distance from the coast, resulting in a medium pollution severity classification (see Table 6.1).

Limiting the probability plot to 5 km from the coast produced a 50% probability value of 502 μS/cm, moving the pollution classification one level higher into the heavy pollution class. Limiting the probability plot to 1 km from the coast resulted in a 50% probability value of 1280 μS/cm, which equates to a very heavy pollution severity level.

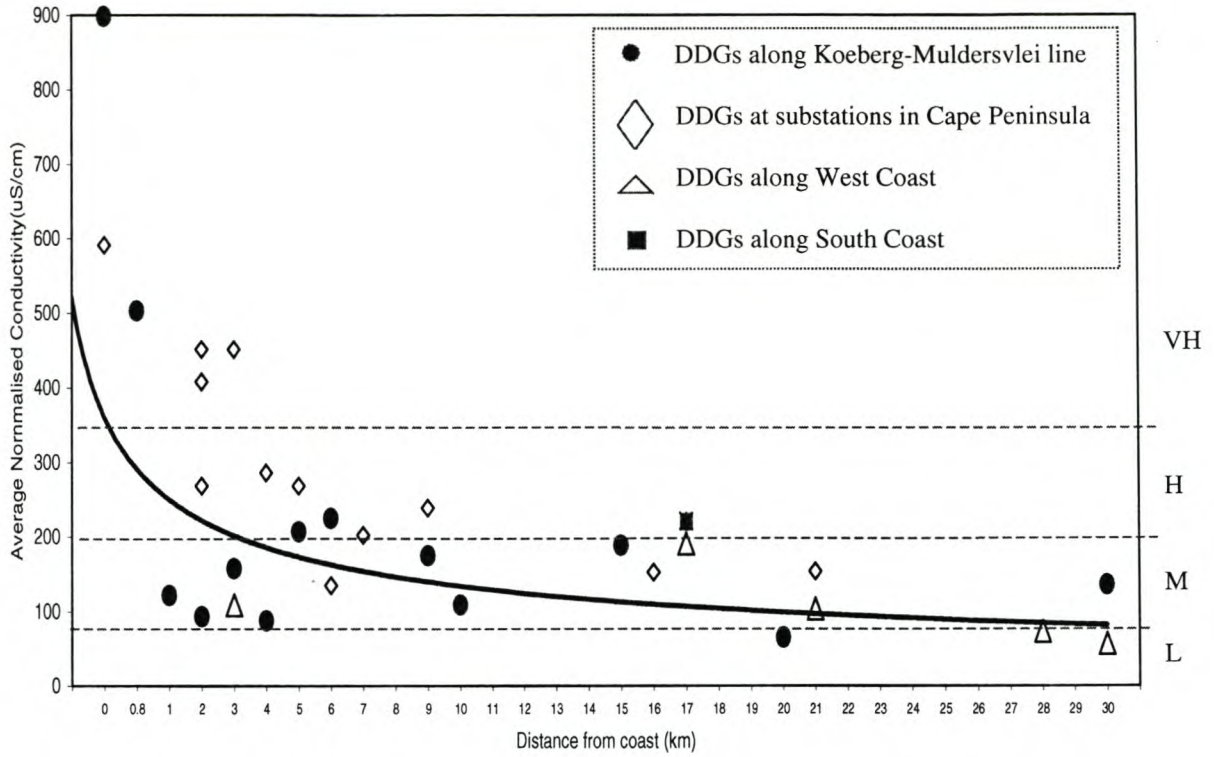

Fig. 6.3 DDG conductivity (average values) in relation to distance-to-coast for test sites in the Cape Peninsula, West coast and South coast.

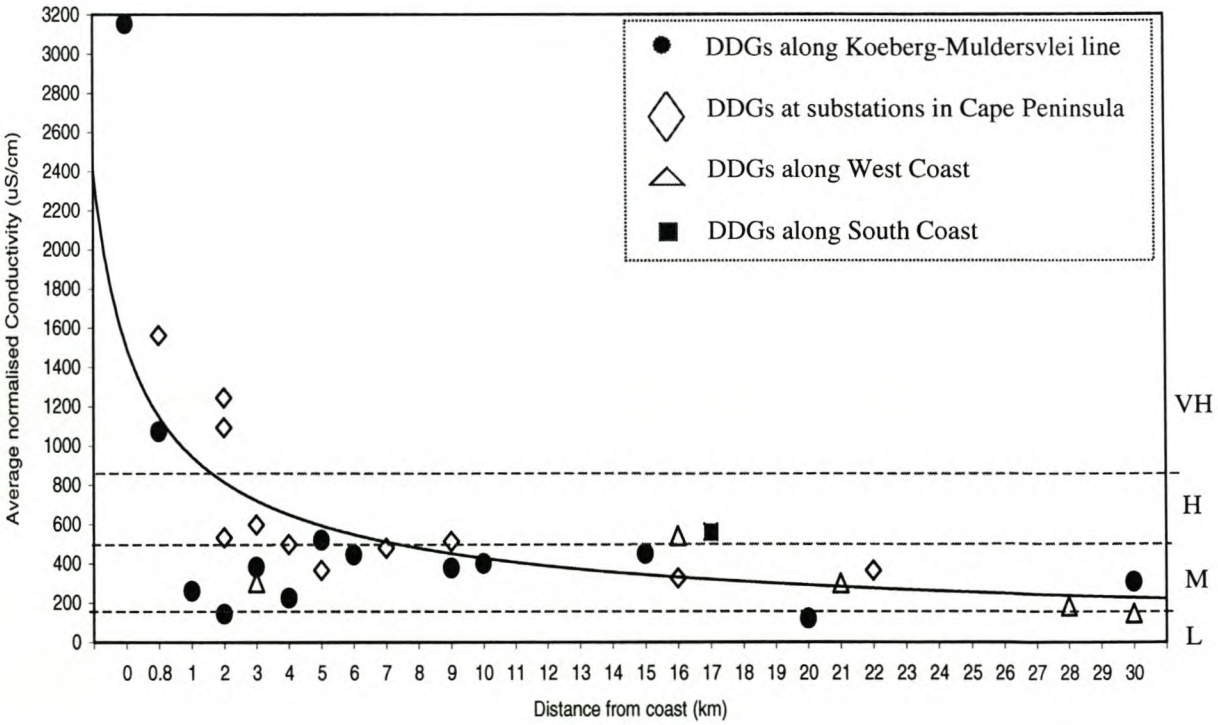

Fig. 6.4 DDG conductivity (maximum values) versus distance-to-coast for test sites in the Cape Peninsula, West coast and South coast.

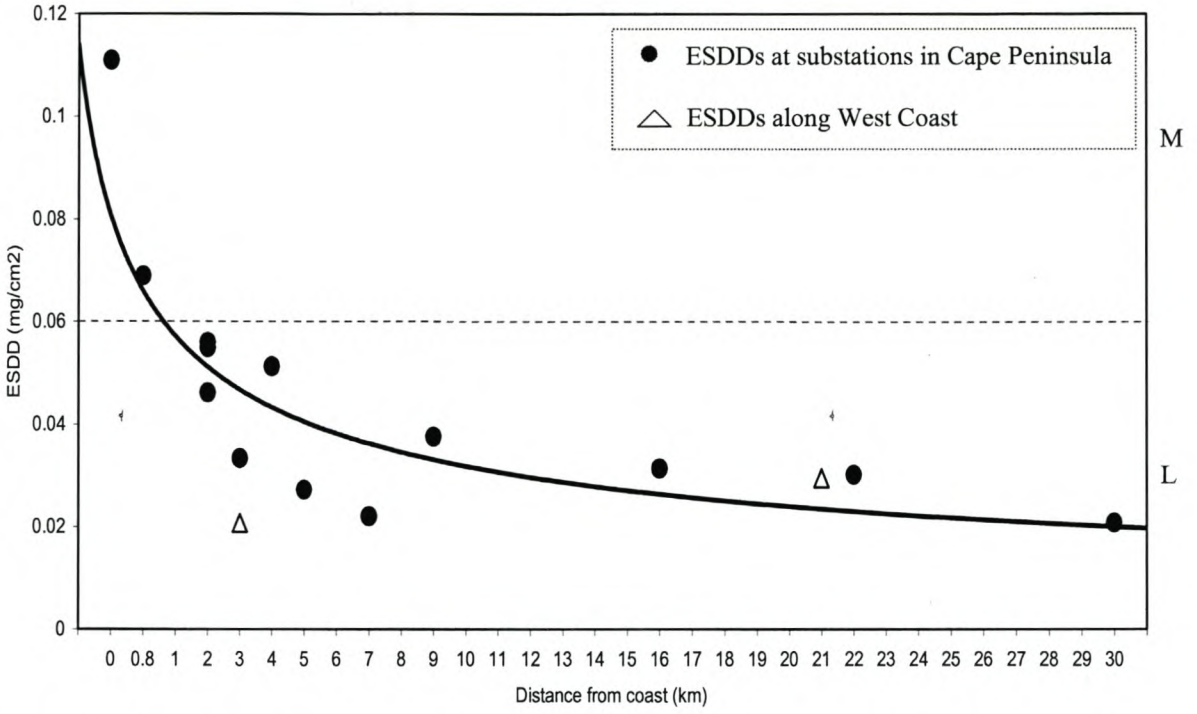

Fig. 6.5 ESDD (average values) in relation to distance-to-coast for test sites in the Cape Peninsula, West coast and South coast.

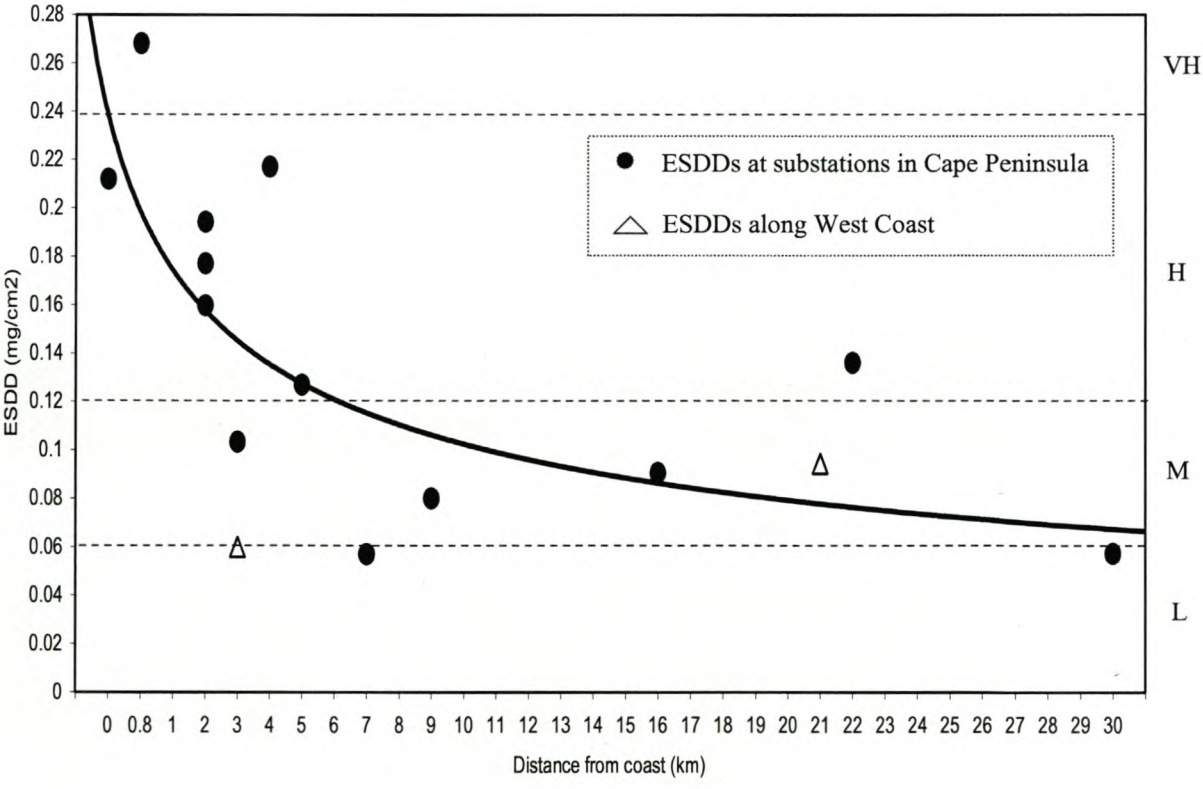

Fig. 6.6 ESDD (maximum values) against distance-to-coast for test sites in the Cape Peninsula, West coast and South coast.

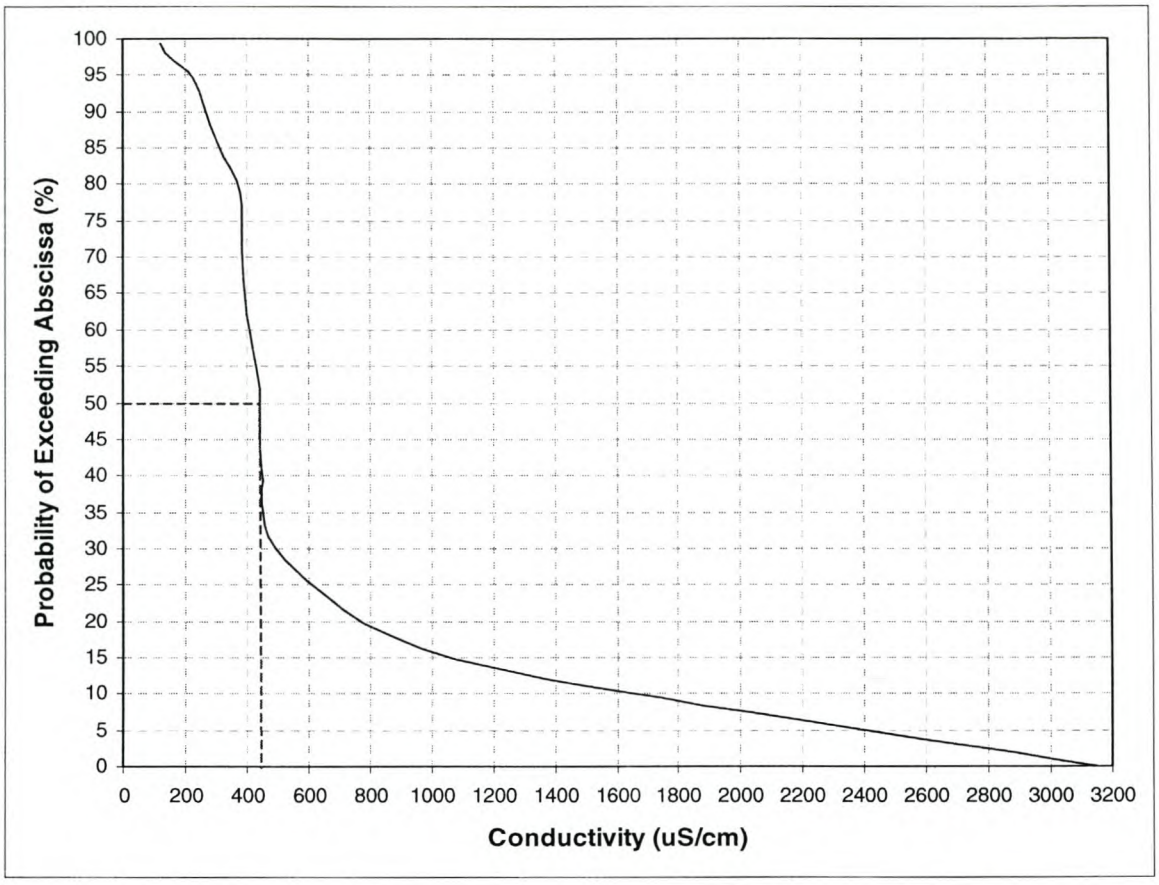

Fig. 6.7 Probability of the maximum DDG conductivity values exceeding a certain value along the 30 km Koeberg-Muldersvlei 400 kV line

6.1.4 Effect of topography: Koeberg-Muldersvlei line

The effect of topography on distance-to-coast DDG pollution levels along the Koeberg-Muldersvlei 400 kV line is illustrated in Figure 6.8.

The topography plot shows no direct relationship between the topography of the line and the DDG pollution measurement results.

The first few hundred metres (up to 500 m) from the coast is fairly flat and open, allowing for easy transportation of the pollution particles (aerosol migration) from the sea; with the direct effect of a very heavy pollution severity level in this zone.

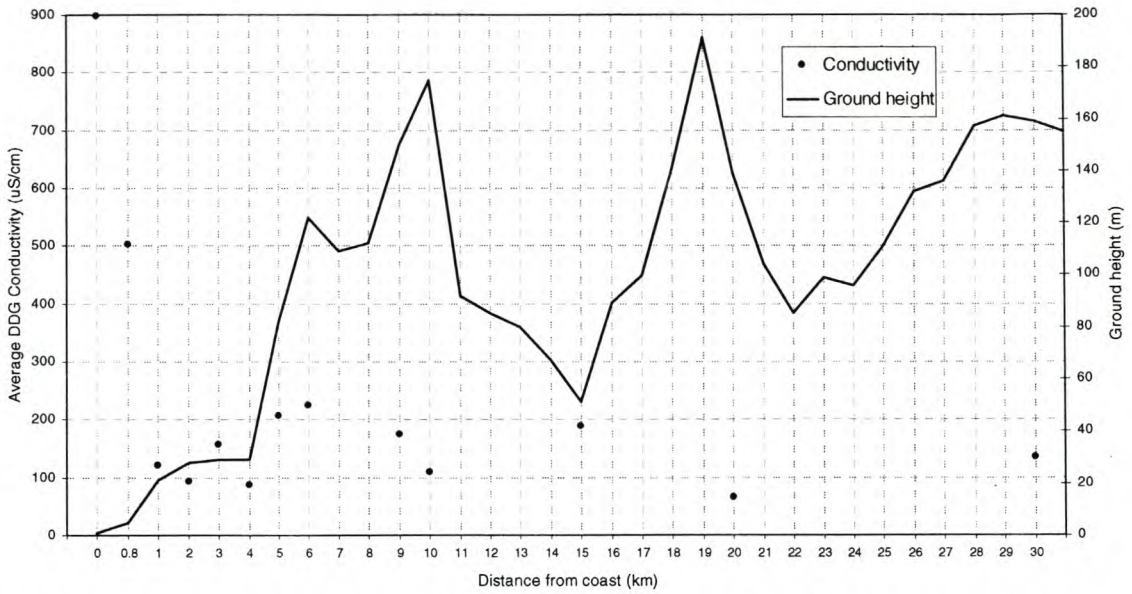

Fig. 6.8 Graph showing average DDG measurements in respect of distance from the coast and height above ground level along the Koeberg-Muldersvlei 400 kV line

Vegetation, growing up to 5 metres high, is located along the coastline from about 1 km to 4 km from the sea. This vegetation acts as a shield and limits the gravitational fall-out of pollution particles in this zone resulting in lower DDG conductivity measurements when compared to monitoring stations located further away (5 and 6 km test sites).

6.1.5 Effect of climatic conditions: Koeberg-Muldersvlei line

Chapter 2 (section 2.1.4) gave a brief discussion of the influence of climatic conditions on insulator pollution severity levels. A detailed description of the climatic conditions prevalent along the West coast, in the vicinity of the Koeberg Weather Station, was given in Chapter 5 (section 5.3).

Table 6.5 is a summary of the climatic parameters recorded at the Koeberg Weather Station between February 2002 and October 2003. Correlations with direct insulator pollution measurement data taken along the Koeberg-Muldersvlei 400kV line for a distance of up to 30 km from the coast (Table 6.2) are discussed below.

Table 6.5: Summary of climatic conditions recorded at the Koeberg Weather station from February 2002 to October 2003

Month	Wind Speed (m/s) Extreme Values			Rainfall (mm)			Temperature (°C)					
							Daily avg			Extreme values		
	Avg	Gust	Direction	Total	Max/24hr	Avg	Max	Min	Avg	Max	Min	Avg
Feb'02	4.6	23.5	158	12.2	8	8.6	26.2	16.4	19.7	35.4	10.9	20.6
Mar'02	3.5	17	162	8.6	5.2	13.7	23.3	15.7	18.6	31.8	8.6	19.2
Apr'02	3	13.6	14	31.6	7.2	32.3	20.9	13.4	16.8	29.8	8.9	16.8
May'02	3.1	18.3	349	25.6	6	49	18.6	11.2	15.8	32.2	4.8	14.8
Jun'02	3.1	17.4	275	53.4	8.2	67.1	16.4	8.6	13.5	26.1	4.5	12.5
Jul'02	3.9	24.3	339	52.8	15.8	70.5	16.3	8.6	13	24.3	3.9	12.5
Aug'02	4.1	22.8	295	62.2	28	51.3	17.8	8.8	13.4	28.2	5	13.3
Sep'02	4	16.9	170	29.4	15.6	34.7	20.2	11.7	14.2	30.2	7.5	15.6
Oct'02	4.5	20.1	273	30.8	10.6	14.9	18.4	11.3	15.8	27.9	6	15
Nov'02	4.2	17.2	189	12	4.4	13.1	19.6	11.7	17.2	34.8	8.4	15.8
Dec'02	4.4	36.9	122	27.6	13.2	14.9	24.7	15.9	15.8	37.4	10.9	19.8
Jan'03	4.2	18.4	180	2.2	1.6	14.9	23.4	15.9	15.8	29	11.5	19.4
Feb'03	3.1	19	180	4.4	3	14.9	23.8	15.8	15.8	35.9	10.1	20.1
Mar'03	2.8	16.7	180	25.6	18.4	14.9	22.3	14.8	15.8	27.6	10	18.4
Apr'03	2.7	17	174	10.2	5.6	14.9	22	14.3	15.8	29.4	9.3	17.5
May'03	3	16.7	320	26.2	11.8	47.1	20.2	11.9	15.1	30.2	6.8	15.6
Jun'03	2.8	12.5	314	12	4.8	64.2	18.3	9	13.5	25.6	5.6	13.3
Jul'03	3.7	16.1	14	33.6	18	63.2	18.2	9.1	13.5	28.1	5.1	13.2
Aug'03	3.9	21.9	238	90.4	29.2	53.4	15.6	7.9	13.3	26.3	4.2	11.8
Sep'03	4	18.8	1	48.6	20.2	35.1	17.9	10.7	14.2	26.2	7.4	14.3
Oct'03	4	17.1	280	11.4	3.2	15.4	21.1	12.7	15.8	36.9	8.3	16.7

6.1.5.1 Wind speed and direction

Wind plays a major role in the transportation and depositing of pollution and moisture on an insulator surface. A relationship between ESDD and wind was found; it showed that an increase in wind speed results in an increase in the pollution deposit to the power three (cubic relationship) [11]. Wind becomes the dominating pollution deposit factor when the wind speed exceeds 2 m/s. Pollution deposit on the insulator is expected on the wind side. Strong winds carrying coarse particles (sand) or rain may remove pollution from the insulator surface [11].

Figure 6.9 illustrates the effect of wind speed (gusts) on DDG pollution levels along the Koeberg-Muldersvlei 400 kV line for the first 5 km from the coast for a period of two years from February 2002 to October 2003. It is evident that there is an increase in pollution levels with an increase in wind speeds (greater than 2 m/s).

Vosloo [21] recorded wind speeds at KIPTS over a year period (12/04/1999 to 12/04/2000) and found that there is a 50% probability that the wind speeds will be higher than 3 m/s (light breeze) during winter and 4.2 m/s (gentle breeze) during summer.

It was also found that the dominant wind during winter is east-north-easterly and south-south-easterly during summer; the strongest winds are north-westerly in winter and south-south-easterly in summer [21]. The results compare well with results obtained from the Koeberg Meteorological station (Table 6.5).

Dust gauge measurements

Appendix E reflects the detail of the dust gauge measurements. The dominant direction was pollution emanating from the east, followed by south, north and west. Summers saw pollution from the east, south and west; while winters produced pollution from the east and north. These results compare well with meteorological findings summarised for the Koeberg-Muldersvlei 400 kV line (see chapter 5, section 5.3.1).

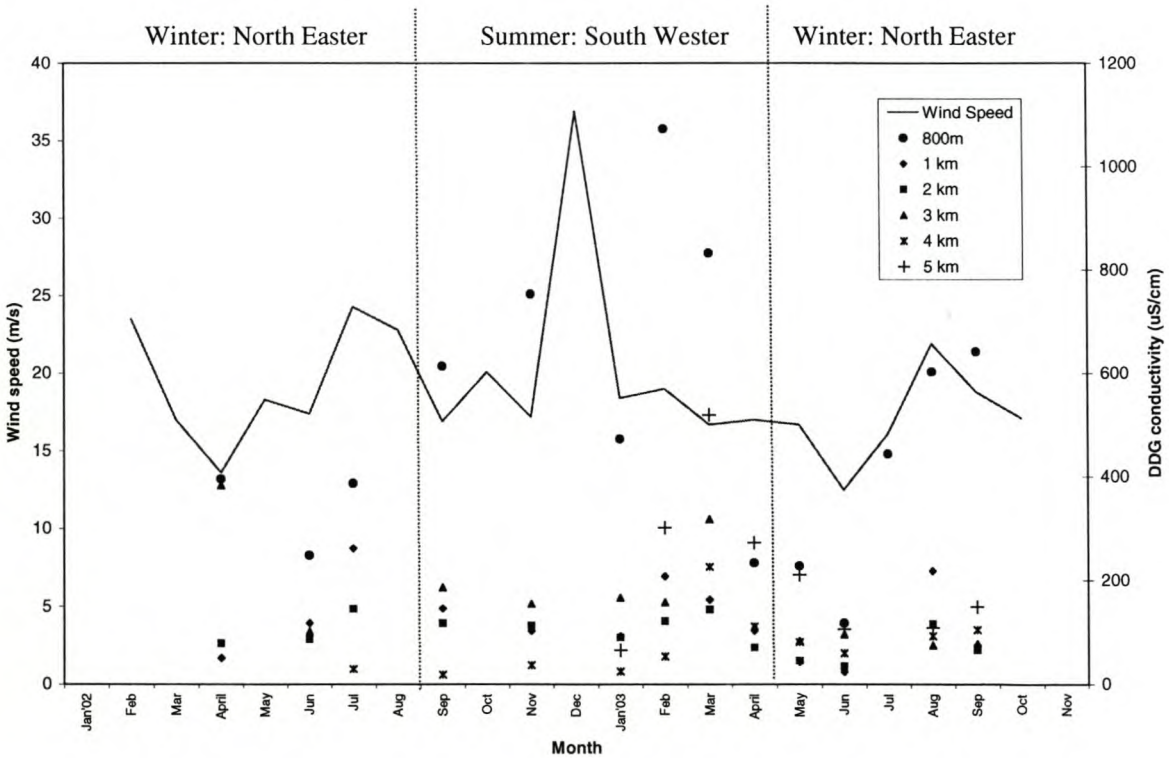

Fig. 6.9 Graph showing the effect of wind speed on DDG pollution levels along the Koeberg-muldersvlei 400 kV line up to 5 km from the coast.

6.1.5.2 Relative Humidity

Relative humidity is an indicator of the moisture level in the atmosphere. When the relative humidity percentage is high (larger than 75%) chances are good that the pollution on the insulator surface could be wetted – resulting in a conductive electrolytic layer, leading to flow and increase of leakage currents. High levels of relative humidity for long periods of time can also result in pollution washing from the insulator surface [21].

Vosloo [21] conducted measurements at KIPTS and found that there is a 50% probability that the relative humidity (RH) will be higher than 94% in winter and 85% in summer. The probability of exceeding an RH of 75% is approximately 88% in winter and 78% in summer. The time-of-day trends show that the average RH levels are above 75% throughout the day. The average RH levels at night are above 90% during winter and above 85% in summer. This means that the probability of critical wetting of the insulator surface is high in both the winter and summer periods

NOTE: There is great danger in trying to find a relationship weather parameters and pollution measurements without substantial scientific proof. The best relationships can only be found with sufficient data. Continuous monitoring at short time intervals (hourly, daily, weekly, monthly) will detect sporadic changes and also record maximum events in weather parameters and pollution levels, which in turn, can be used for correlation studies. With this background in mind, it was found that the IPMR (Insulator Pollution Monitoring Relay) would be best suited [80]. The IPMR determines the pollution severity by measuring the surface conductivity on the test insulator. The test insulator is part of the IPMR unit. The IPMR can be used to develop a dynamic insulator pollution severity application map (DIPSAM) for South Africa. By installing the IPMRs covering a good spatial spread of South Africa, the information can be fed into a central database and a dynamic map can be made available after every download.

6.2 CORROSION TESTING RESULTS

This section discusses corrosion testing results obtained along the Koeberg-Muldersvlei 400 kV line. The test methodologies were discussed in chapter 3 (section 3.2), covering two test methods: CLIMAT and metal specimen testing. The choice and location of the test sites were discussed in chapter 5, section 5.1.3 and Figure 5.1.

The relationship between the corrosion classes and the corrosion severity index for CLIMAT and the metal specimens is provided in Table 6.6.

Table 6.6: Corrosion index in relation to corrosion severity class

Corrosion severity class	Corrosion category	Corrosion Index, CI (µm/y)			
		CLIMAT		Metal Specimens	
		Al-Fe	Al-Cu	Mild Fe	Galv Fe
Very low	C1	≤ 1.3	≤ 0.1	≤ 1.3	≤ 0.1
Low	C2	1.4 to 25	0.2 to 0.6	1.4 to 25	0.2 to 0.7
Medium	C3	26 to 50	0.7 to 1.3	26 to 50	0.8 to 2.1
High	C4	51 to 80	1.4 to 2.8	51 to 80	2.2 to 4.2
Very High	C5	> 80	> 2.8	81 to 200	4.3 to 8.4

6.2.1 Receptor specimens: Koeberg-Muldersvlei line

Specimens were installed in March (1, 2, 3, 4, 9, 10, 20km), April (KIPTS, 10km), and May 2003 (15, 30km). CLIMAT testers were recovered after an average of 97 days and the metal coupons after 214 days.

The following specimens were exposed at each of the 13 sites:

- Mild Steel (100 x 50 x 3.0mm), nominally 200 grade, of composition C 0.18, Mn 1.02, Si 0.04, P 0.028, and S 0.015%.
- Galvanised steel (150 x 100 x 0.64mm), the passivation treatment after galvanising was a chromic acid type resulting in a surface chromium level of 17mg/m^2.
- CLIMAT testers as described in chapter 3 (section 3.2.2).

6.2.2 General trends in corrosion rates: Koeberg-Muldersvlei line

Table 6.7 is a summary of the corrosion rates (in µm/y) recorded along the Koeberg-Muldersvlei 400 kV line. Included in the table is the distance of each site from the sea, the height above ground level for each site, the corrosion rates, and a description of specific pollution sources. Detail corrosion test results are provided in Appendix G.

King *et al* reported salt deposition close to the coast (within 10^3 m) is highly influenced by salt production at surf beaches and by local terrain, whilst salt at 10^3 m to 10^6 m inland is more influenced by transport of the finer aerosol produced by ocean white caps [3].

Plots of corrosion rates versus distance-to-coast along the Koeberg-Muldersvlei 400 kV line for CLIMAT, mild steel, and galvanised steel is given in Figure 6.10, 6.11 and 6.12 respectively. The corrosion rate decreases dramatically (a sharp decline) within the first kilometre from the sea and remains fairly linear up to 30 km from the coast. It is also evident that the order of magnitude for pollution levels close to the coast (up to 1 km) is twice (or even 3 times) that of pollution levels further inland, which agrees well with findings from various distance-to-coast corrosion studies [50], [51], [52], [53].

More detail discussion on the CLIMAT and Metal specimen test results are given in the following sections.

Table 6.7: Corrosion measurements for the distance-to-coast study along the Koeberg-Muldersvlei 400 kV line

Site No.	Description (see footnote in parantheses)	Height above sea level (m)	Distance to sea (km)	CORROSION RATES (um/y)			
				CLIMAT		Metal Coupons	
				Al-Fe	Al-Cu	Mild Fe	Galvanised Fe
1	Severe marine (3)	1	**0.05** KIPTS			56.338	5.490
						High	Very High
2	Severe marine (2), (3)	5	**0.8** KWS	51.76		20.087	1.582
				High		Low	Medium
3	Marine (1)	21	**1**	69.39	17.856	17.922	0.188
				High	Very High	Low	Low
4	Traffic (1)	28	**2**	21.20	1.830	15.588	1.008
				Low	High	Low	Medium
5	Vegetation	29	**3**	31.10	2.234	4.197	0.754
				Medium	High	Low	Medium
6	Vegetation	29	**4**	23.97	1.396	12.575	0.896
				Low	Medium	Low	Medium
7		82	**5**	25.10	2.549	10.431	1.246
				Medium	High	Low	Medium
8		122	**6**	45.60	1.909	3.491	0.974
				Medium	High	Low	Medium
9	Traffic (2)	150	**9**	5.60	0.491	3.965	0.547
				Low	Low	Low	Low
10		175	**10**	25.08	2.760	4.219	0.501
				Medium	High	Low	Low
11	Traffic (2)	51	**15**	22.98	1.457	1.689	0.736
				Low	High	Low	Medium
12	Mild industrial (2)	139	**20**	16.35	1.904	7.754	0.035
				Low	High	Low	Very Low
13	Traffic (2)	159	**30**	6.18	0.627	10.969	1.594
				Low	Medium	Low	Medium
Mean				**28.69**	**3.183**	**13.985**	**1.1891**
				Medium	**Very High**	**Low**	**Medium**
Standard Deviation				**18.609**	**4.9176**	**13.837**	**1.3735**

1. Strictly moderately severe marine
2. Extremely close to heavily trafficked road or freeway
3. Site at low elevation (<20m), very flat and exposed terrain

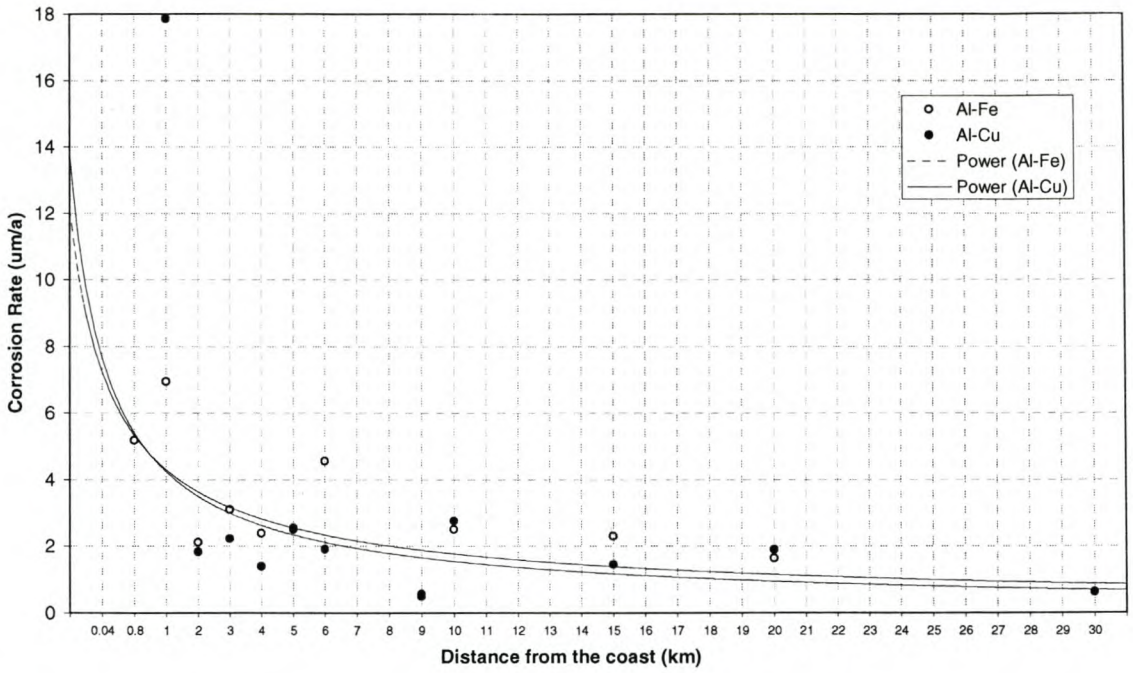

Fig. 6.10 Graph showing the effect of distance-to-coast on CLIMAT corrosion rates along the Koeberg-Muldersvlei 400 kV line

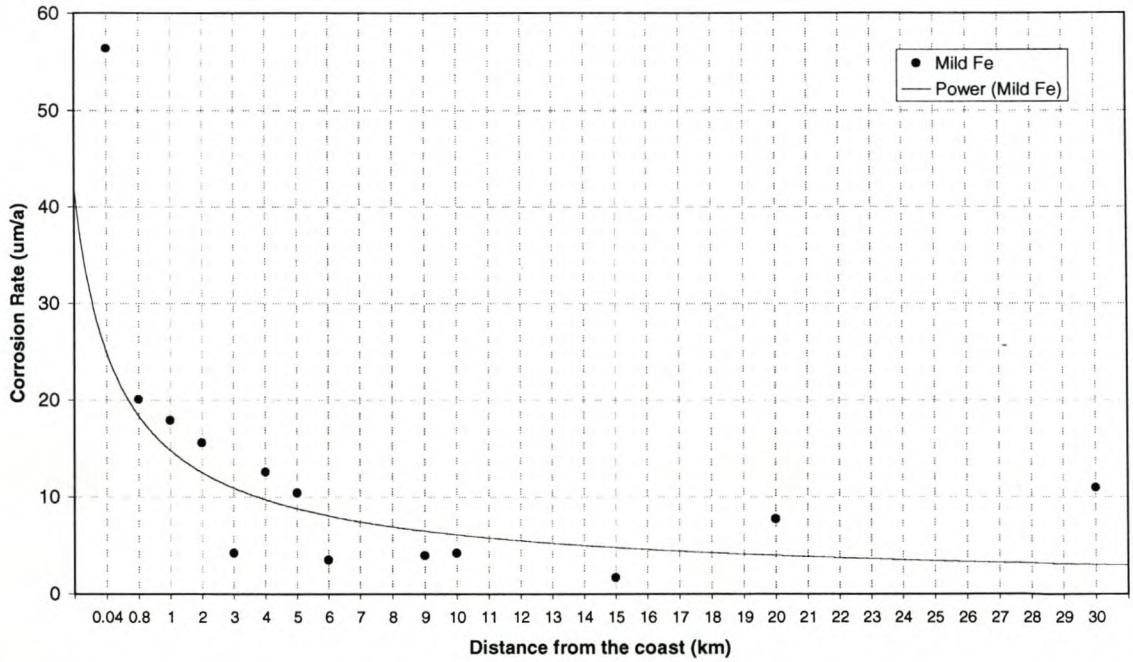

Fig. 6.11 Graph showing the effect of distance-to-coast on mild steel corrosion rates along the Koeberg-Muldersvlei 400 kV line

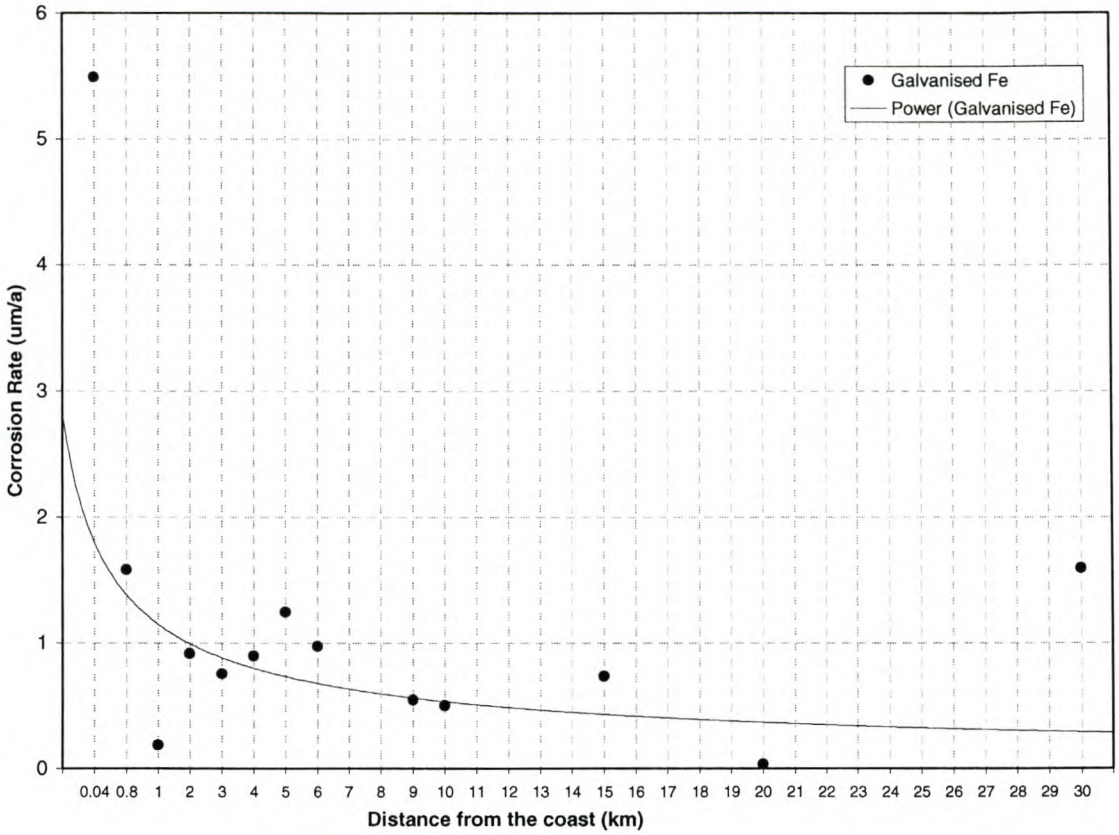

Fig. 6.12 Graph showing the effect of distance-to-coast on galvanised steel corrosion rates along the Koeberg-Muldersvlei 400 kV line

6.2.3 CLIMAT corrosion rates: Koeberg-Muldersvlei line

The CLIMAT (or 'wire-on-bolt') test is a dissimilar metal test consisting of an aluminium-copper (Al-Cu), aluminium-steel (Al-Fe), and aluminium-nylon assembly. The test methodology was discussed in chapter 3, section 3.2.2.

6.2.3.1 Effect of distance-to-coast

The specimens at the coastal test site (KIPTS, 50m from the beachfront) could not be assessed since sections of the aluminium wire broke off. According to ASTM Practice G116 [24], if any sections of the wire are sufficiently corroded to have dropped out of the assembly, then the test is invalid and a shorter duration of exposure should be chosen for a retest.

Although no retesting was done and no mass loss or corrosion rate was obtained at KIPTS for the CLIMAT test (see Table 6.6) the fact that the exposure period was too long for the KIPTS test site when compared to the other test sites further inland is indicative of the harsh and aggressive environment and the accelerated corrosion rates at the coast.

6.2.3.2 Galvanic effect

AL-CU assembly

From Table 6.6 it is also noticed that the CLIMAT test for the Al-Cu assembly produced corrosion rates in the **very high (C5) and high (C4)** category, see Table 3.3. This is attributed to the big difference in the galvanic value between aluminium (-1.67V) and copper (+0.13V), see chapter 2 and Table 2.1, which results in an accelerated corrosion activity.

AL-FE assembly

For the Al-Fe assembly the galvanic difference is much smaller (mild steel at -0.44V) when compared to the Al-Cu combination, consequently resulting in a lower corrosion rate and producing corrosion categories ranging between **low (C2) and medium (C3)**.

6.2.3.3 Effect of exposure duration

Two exposure durations were investigated for the CLIMAT test: a 90-day and 180-day test. Results are discussed below.

90-day exposure

For the 90-day exposure test (see Appendix G), specimens were exposed to the atmosphere for an average of 95 days. Detail of the assembly was discussed in chapter 3, section 3.2.2 (see figure 3.3).The first specimens were installed in March 2003 and removed in May 2003, and the last specimens were installed in May 2003 and removed in August 2003.

The highest mass loss was recorded at the test sites closest to the coast (2 and 3 km). The aluminium wire broke off from the test assembly for test sites within 1 km from the coast (due to the higher corrosion rates) but for the same period of exposure none of the

aluminium wires broke off for test sites further than 1 km from the coast (signifying lower corrosion levels in this zone).

190-day exposure

It was the author's intention to determine whether the corrosion rate changes significantly with a longer exposure duration. In order to answer this question a second test specimen was installed at each test site (see figure 3.3.) and exposed for an average of 190 days.

Upon removal of the 190-day CLIMAT specimens it was found that sections of aluminium wire were broken off for all the test sites within five kilometres from the coast. As discussed above, this condition renders the test invalid [24] and retesting is recommended. The results from the 190-day exposure test indicate that a higher mass loss can be expected for longer exposure durations. This does not, however, imply that the corrosion rate necessarily increase for longer exposure durations.

Findings: 90-day versus 190-day exposure

The 190-day exposure duration has been found to give a similar corrosion rate as that for the 90-day exposure test, but assessment and cleaning was much more difficult. It is therefore not recommended to do a CLIMAT test with exposure durations of more than 90 days.

The ASTM G116 Practice [24] recommends exposure durations of 90-day intervals, changing the specimens after 90 days until a 270-day exposure cycle is completed. Each 90-day test specimen must then be separately analysed. This approach has been found to be more accurate in representing seasonal variations in corrosion rates.

6.2.4 Metal specimen corrosion rates: Koeberg-Muldersvlei line

Metal specimens (flat metal coupons) were exposed to the atmosphere for an average of 214 days and constituted a mild steel (Fe) and galvanised steel exposure test. The first specimens were installed in March 2003 and the last specimens were removed in November 2003. The test methodology was discussed in chapter three (see section 3.2.3) and the detailed corrosion test results are provided in Appendix G.

6.2.4.1 Mild steel corrosion results

From Table 6.6 and Figure 6.11 it is shown that the highest corrosion rate (56.338 µm/y) for the mild steel (mild Fe) test was recorded at KIPTS (50 m from the beachfront); with the second highest value (20.088 µm/y) recorded at the test site second furthest from the beachfront (Koeberg Weather station, 800m from the sea). The corrosion category (see chapter 3, Table 3.2) for KIPTS and the Koeberg Weather station is high (C4). The test sites located further inland (between 1 and 30 km from the sea) have a very linear corrosion profile (Figure 6.10) with all sites recording a low (C2) corrosion category.

A significant finding is the fact that the corrosion class dropped with two levels over the first 800m from the seacoast, from high (C4) to low (C2).

6.2.4.2 Galvanised steel corrosion results

Figure 6.12 and Table 6.6 indicate the highest corrosion rate (5.49 µm/y) for the galvanised steel test was recorded at the KIPTS test site (closest test site to the seacoast); producing a high (C4) corrosion level. The test site located second furthest from the sea (Koeberg Weather Station) recorded the second highest corrosion rate (1.58 µm/y), placing this site in the medium (C3) corrosion category.

A linear profile, as in the case of the mild steel test, is noted for all test sites further than 1 km (up to 30 km) from the coast. The corrosion category varies between low (C2) and medium (C3) for the test sites within this zone.

A significant point to note is the fact that the corrosion class at the coastal test site (KIPTS) is very high (C5), while the next station (located 800 m from the sea) recorded a corrosion level that is two categories lower, medium (C3).

6.2.5 Effect of climatic conditions on corrosion indices

As mentioned in chapter 2 (section 2.2.6), corrosion takes place during the time of wetness (TOW). This phrase refers to the period during which the surface is covered by a film of water (electrolyte) that permits appreciable corrosion to take place. The TOW is dependent upon the frequency of rain, fog, dew, the temperature of the air, relative humidity of the atmosphere, the wind speed, and the hours of sunshine. For corrosion, the temperature of the metal is also a factor [39].

The behaviour of steel in the atmosphere depends to a great extent on the concentration of pollutant agents and humidity. At 25°C, steel is very stable if the relative humidity is below 70% (critical humidity) [22].

Industrial atmosphere is a polluted one containing mainly sulphur compounds that make atmospheric corrosion worse. The sulphurous compounds (i.e., sulphur dioxide [SO_2]) act directly as cathodic depolarizers, being reduced in the process. Also, by dissolving, these compounds increase the acidity of the acidity of humidity on the metal surface. Table 6.8 shows the combined effect of humidity and SO_2 on the steel corrosion rate, as determined under laboratory conditions [22].

Table 6.8: Corrosion rates of unalloyed steel in atmospheres polluted by SO_2 [22].

Atmosphere	**Pure Air**	**Air + 2% SO_2**	**Air + 5% SO_2**	**Air + 5% SO_2 + 5% H_2O**
Corrosion rate (µm/y)	1	1.18	1.35	2.76

It is noted from Table 6.8 that a small increase in SO_2 results in a significant increase in the corrosion rate; the corrosion rate double with the addition of water.

Marine atmosphere is chactarised by chlorides contained in the marine aerosols and by high relative humidity, >90%. The salts remaining on the surface of metals after evaporation contain chloride ion, which is aggressive to the passivating superficial layers. They also are hygroscopic, retaining humidity on the metallic surface [22].

Vosloo conducted a study at the KIPTS test site and found that there is a 50% probability that RH will be higher than 94% in winter and 85% in summer. The probability that the RH levels will exceed 75% is approximately 88% in winter and 78% in summer [21]. Corrosion rates are significantly increased at RH levels above 75%, which also explains why the distance-to-coast corrosion plots are similar in profile (see figures 6.10 to 6.12), high to very high for test sites close to the coast (within 1000m) with a sharp decline moving inland.

6.2.5.1 Atmospheric characterisation methods

Since atmospheric corrosion is considered a *discontinuous* process (because an electrolyte is not always present), correlation studies to determine the direct effect of each climatic parameter is somewhat difficult. The ASTM Practice G92 [31] for conducting atmospheric characterisation of the test sites suggests two methods of testing: Method A, the use of metal specimens and, Method B, atmospheric monitoring methods. The two methods are briefly discussed below.

Method A: Flat metal specimens

This method was discussed in chapter 3 (section 3.2.3). The results obtained from test sites along the Koeberg-Muldersvlei 400 kV line (up to 30 km inland from the coast) as part of a distance-to-coast study was discussed in section 6.2.4.

Method B: Atmospheric monitoring

Several atmospheric factors (temperature, relative humidity, precipitation, and time-of-wetness) have been identified as having a significant influence on the corrosion of metals and deterioration of materials. The atmospheric factors to be monitored are dependent on individual needs, and at what frequency the monitoring devices can be attended. Daily attention is often preferred. Suggestions for monitoring systems requiring minimal attention are listed in Table 6.9 [31].

Table 6.9: Recommended methods for monitoring atmospheric factors [31]

	Atmospheric Factors	**Monitoring Device**
1	Sulphur dioxide	Sulfation plate, [30]
2	Chloride content	Wet (salt) candle, [33]
3	Temperature/humidity	Hygrothermograph (combination of hygrograph and thermograph used for recording temperature and humidity)
4	Precipitation	Standard 200 mm rain/snow gauge (periodic sampling for pH range)
5	Time of wetness	Cu/Au sensor (procedure defined in practice G84), [29]
6	Climatological data	National weather service (bureau)

Hourly, daily, weekly and monthly variations in the atmospheric factors are intimately linked with the corrosion process. Quantitizing these changes can provide insight into the corrosion performance [31]. This study did not make provision for direct correlations of climatic conditions with corrosion rates due to the intensity of such an exercise, it is nonetheless recommended.

Atmospheric monitoring should be performed at a site as near to the placement of the corrosion specimens exposed in Method A as possible. Microclimatological variations at a given test area could reasonably be expected to exist and thus close proximity of the two methods is important.

NOTE: Only Method A, flat metal specimens (section 6.2.4), were used for characterisation of the atmosphere. Another exposure method, the CLIMAT test was also used (see section 6.2.3).

6.3 CORRELATION STUDIES

Table 6.10 is a summary of regression analyses for test sites along the Koeberg-Muldersvlei 400kV line and Cape Peninsula (see Figure 5.1), and along the West and South coast (see Figure 6.2). A very strong relationship exists between DDG pollution levels, distance from the coast and mild steel corrosion rates with an R^2 value of 0.75. The test results produced a moderate linear relationship between DDG and ESDD with an R^2 value of 0.62.

Figures 6.13 to 6.15 are plots from regression studies for various measurement parameters with the regression forced through the origin. A hypothesis test (t-test) was carried out to determine the usefulness of the relationship. A P-value greater than 0.01 (P>0.01) indicate that there is no useful linear relationship between the modelled parameters, see Table 6.10.

It should be noted that the data point appearing as an outlier (Figure 6.13 to 6.15) is not an outlier in the true sense of the word, but rather the correlation values for KIPTS, the closest test site to the sea. The difference in pollution values between the coastal station (KIPTS, at 40 m from the sea) and the next test site (Koeberg Weather station, 800m from the coast) is in the order of 2 to 3 times in magnitude, showing a significant decline in pollution severity in this zone. It would be a better approach to have more monitoring stations over the first few hundred meters from the coast (up to 1km) to capture the declining pollution values in this zone.

To the author's knowledge no other study have been carried out whereby direct insulator pollution measurements were correlated with corrosion testing results.

Table 6.10: Correlation parameters for test sites along the Koeberg-Muldersvlei line

Description		R^2	Standard error	Slope, b	P -value
DDG vs ESDD	avg	0.617322	0.0147	0.0001099	9.06158×10^{-5}
	max	**-0.608362**	**0.08419**	**0.000118**	**4.64×10^{-5}**
DDG vs mild Fe	avg	0.7558815	7.07787	0.060688	2.59×10^{-6}
	max	**0.748623**	**7.182327**	**0.01489**	**3.05×10^{-6}**
DDG vs CLIMAT	avg	-0.111266	1.9617	0.013788	0.000431
	max	**-0.132**	**1.979958**	**0.006093**	**0.000479**
Mild Fe vs CLIMAT (Al-Fe)		-0.446458	6.0517	2.8534	0.000581
CLIMAT vs CLIMAT (Al-Fe vs Al-Cu)		0.589449	3.150925	1.518899	0.000493

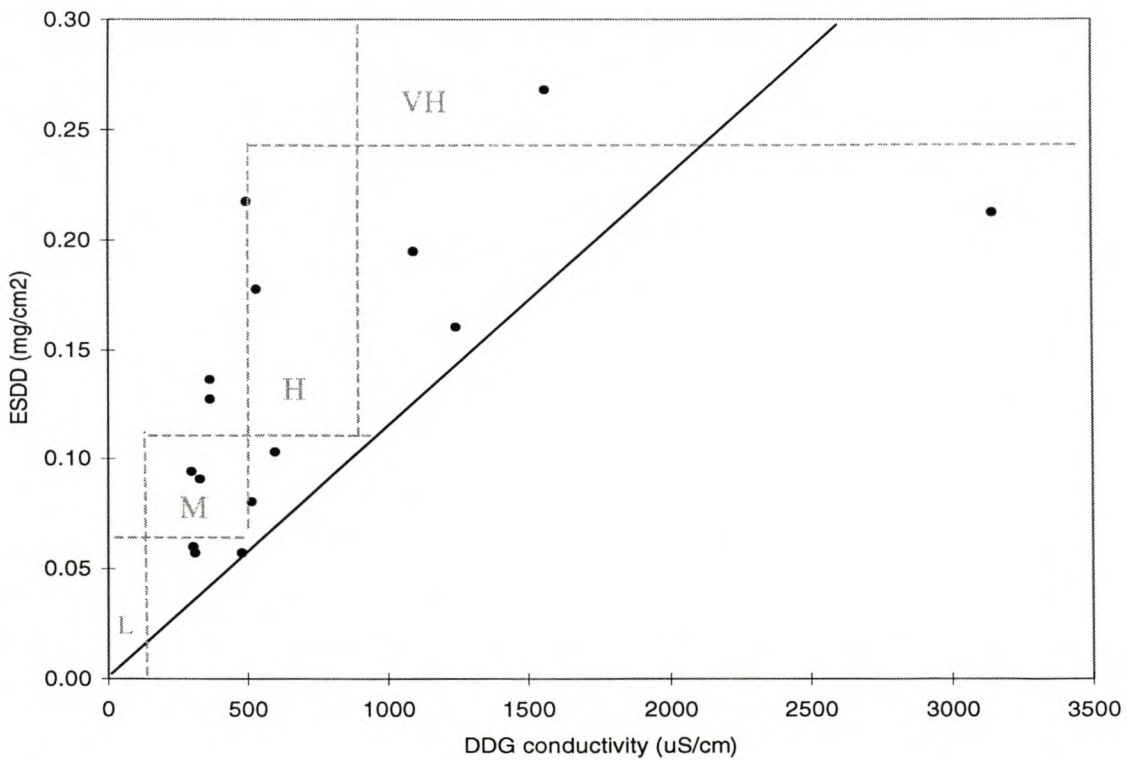

Fig. 6.13 Correlation between ESDD and DDG measurements (maximum values) recorded for test sites along the Koeberg-Muldersvlei 400 kV line.

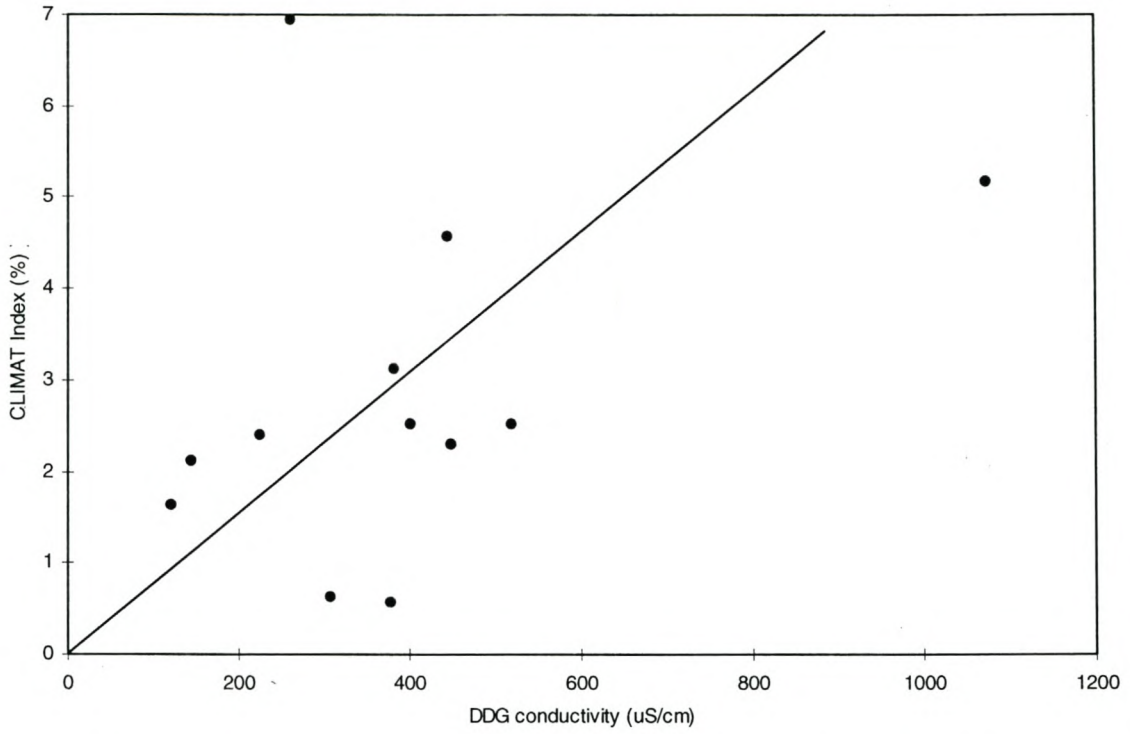

Fig. 6.14 Correlation between DDG (maximum values) and CLIMAT (Al-Fe) results for test sites along the Koeberg-Muldersvlei 400 kV line.

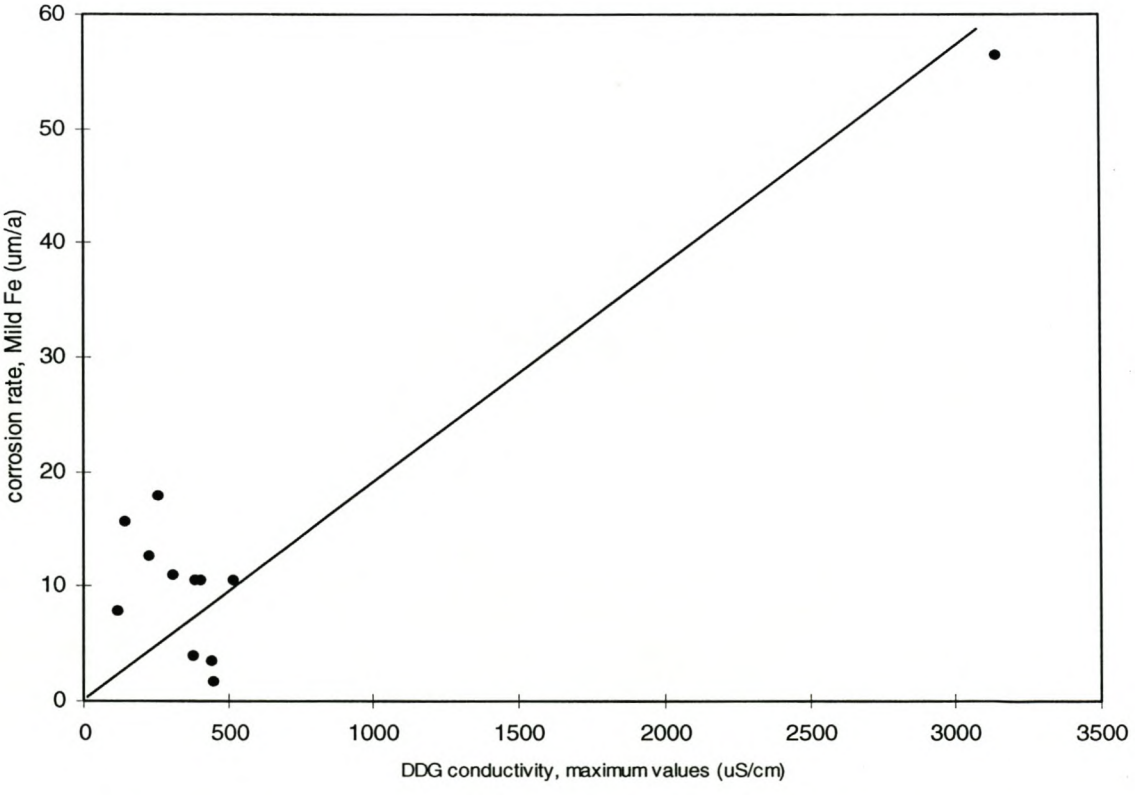

Fig. 6.15 Correlation between DDG (maximum values) and Mild Fe results for test sites along the Koeberg-Muldersvlei 400 kV line.

6.4 IMPACT DISTANCE

The pollutants at KIPTS were found to be predominantly sodium chloride (NaCl) [21], with the sea as the source of the salt-laden aerosol and affecting areas further inland.

Table 6.11 is a summary of the impact distance for each pollution level based on the distance-to-coast analysis. It should be noted that pollution levels could penetrate further than indicated; however, the impact distances are reflective of the actual measurements.

Table 6.11: Impact distance for pollution severity classes

Description		**Maximum distance of impact (km)**			
Insulator Pollution Index, PI		**Very Heavy**	**Heavy**	**Medium**	**Light**
Corrosion Index, CI		**C5**	**C4**	**C3**	**C2**
DDG	max	5	17	30	>30
	Avg	5	17	30	>30
ESDD	max	0.8	22	30	> 30
	avg			0.8	> 0.8
Mild steel			0.05 (KIPTS)		30
Galvanised steel		0.05		30	> 30
CLIMAT (Al-Fe)			1		30
CLIMAT (Al-Cu)		1	20	30	> 30

From Table 6.11, it is shown that the impact distance to the sea very heavy pollution is 5km, and 17km for heavy pollution based on the DDG test method, whereas for ESDD, very heavy pollution only penetrate 0.8km.

The CLIMAT (Al-Cu) test has a very high corrosivity that reaches up to 1km from the coast, whereas Galvanised steel only reaches up to 50m (KIPTS) from the coast for the same corrosivity index.

6.5 SUMMARY

Figure 6.3 and 6.4 is a summary of all the DDG (average values) and ESDD (average values) measurements respectively recorded in the along the Koeberg-Muldersvlei 400kV line, the Cape Peninsula, the West and South Coast, and (see Tables 6.2, 6.3, and 6.4).

Corrosion results from test sites along the Koeberg-Muldersvlei line is summarised in Figure 6.10 and 6.11 for CLIMAT (aluminium-steel and aluminium-copper assemblies) and metal specimen tests (mild steel and Galvanised steel) respectively for a distance of up to 30 km from the sea (see Table 6.7).

From Figure 6.3, 6.4, 6.5, 6.6, 6.10 and 6.11, it is clear that the order of magnitude of pollution levels for test sites close to the coast (within 1 km) is twice (or even 3 times) that of sites further inland. A steep decline in pollution severity and corrosion rates are noticed over the first 10^3 m from the coast, with the profile becoming more stable for test sites further inland.

Correlations studies produced a very strong relationship between DDG pollution levels, distance from the coast and mild steel corrosion rates with an R^2 value of 0.75.

Very heavy pollution levels were found to penetrate up to a distance of 5 km from the coast for the DDG insulator pollution tests, and up to 800 m for ESDD tests.

The corrosivity indices for the CLIMAT (Al-Cu) test was very high for a distance of up to 1 km from the sea, while for the flat metal specimen (galvanised steel) the impact distance was 50 m (KIPTS) for the same corrosivity index.

It is recommended that a model be developed based on multiple regression analysis (distance-to-coast, topography, %RH, cloud height, wind speed, chloride content, and corrosion rate) to predict corrosion rates [53].

It is further recommended that multiple regression analysis be used to develop a model to predict insulator pollution severity levels based on corrosion rates.

6.6 CONCLUDING REMARKS

The results from the distance-to-coast study show an exceptional pollution severity over the first 500 to 800 meters from the coast; thereafter a rapid decay is noticeable moving further inland.

The DDG and ESDD pollution tests produced very heavy pollution severity levels with an impact distance from the sea of 5 km and 800 m respectively. The difference in the test results is ascribed to the type of test method used; where the DDG test is a cumulative test also containing the maximum event, while the ESDD test is a snapshot with the likelihood of not capturing a maximum event due to natural washing.

A very high corrosivity index with an impact distance from the coast of 1 km and 50 m were recorded for the CLIMAT (Al-Cu) and flat metal specimen (galvanised steel) corrosion tests respectively.

Corrosion rates and insulator pollution levels were found to be 2-3 times higher for the test sites located within the first 1000m from the coast compared to test sites located further inland.

There was no direct relationship found between the topography of the test stations and the DDG pollution measurement results; is it rather the closeness of the pollution sources to the test sites that have a greater impact. The first few hundred metres (up to 500 m) from the coast is fairly flat and open, allowing for easy transportation of the pollution particles (aerosol migration) from the sea; with the direct effect of a very heavy pollution severity level in this zone. It was also found that the vegetation, especially where trees are densely populated and grow higher than 3 m from the ground, could significantly influence the measurements (for example in the zone between 1 and 4 km from the coast on the Koeberg-Muldersvlei 400 kV line.)

The Koeberg-Muldersvlei 400kV line is located in a winter rainfall area with dry summers. The DDG pollution levels that were recorded along this line show that pollution levels are generally higher during periods of low rainfall (dry spells), September 2002 to March 2003. The most important influence – that of wind direction – is amplified by the advantage of the directional measurement of the dust gauge; the highest pollution levels

were recorded for the westerly and southerly directions in summer, while for winter the easterly and northerly directions predominantly produced higher results.

Relative humidity (RH) and time-of-wetness (TOW) is the dominant climatic factors resulting in increased insulator surface wetting, which in turn leads to increased leakage current activity. RH and TOW also leads to an increase in corrosion rates. For the Koeberg-Muldersvlei test area, the relative humidity is higher than 80% for both summer and winter periods along the west coast for a distance of up to 500m from the coast; the probability of critical wetting of the insulator surface is high in both winter and summer periods. The high RH value also results in significant higher corrosion rates over the first few hundred metres (up to 1000m); corrosion rates are twice (or even 3 times) as high at the coast compared to sites further inland.

A very strong relationship have been developed between DDG pollution levels, distance from the coast, and mild steel corrosivity with an R^2 value of 0.75. A moderate linear relationship between DDG and ESDD pollution values were found with an R^2 value of 0.62. It can therefore be concluded that a corrosion map can be used to predict insulator pollution severity levels in the case where direct insulator pollution measurements are not available, or vice versa.

It is recommended that a model be developed based on multiple regression analysis (distance-to-coast, topography, %RH, cloud height, wind speed, chloride content, and corrosion rate) to predict corrosion rates [53].

HEIGHT-ABOVE-GROUND MEASUREMENTS

Another primary objective of this study was to determine the effect of height-above-ground on insulator pollution severity levels and corrosion rates. A 120m high weather mast was used for this exercise. This chapter describes the philosophy behind the test site selection and the test methodology focusing on the setting up procedure and the exposure durations.

The discussion is further extended to include measurement results from dust gauges (DDG) and corrosion tests on the 120m high mast. Correlation results, to determine the relationships between the two methods, are also included.

7.1 SITE SELECTION: 120M HIGH WEATHER MAST

The key criterion for the execution of this part of the study was to find a suitable site to install dust gauges and corrosion specimens at various heights. The location had to be close to the coast (marine pollution source), secure and free from vandalism.

The 120m high weather mast located at the Koeberg Weather Station (KWS) was investigated and found to be ideal for height-above-ground insulator pollution measurements and corrosion exposure tests. This mast is used by the weather bureau for meteorological measurements of rainfall, pressure, wind, and temperature. Meteorological data is recorded at various heights: 10m, 50m, 85m, and 120m. The weather station (weather mast) is located approximately 800 m from the shoreline.

7.2 TEST METHODOLOGY

It was decided to install dust gauges and corrosion specimens at the same heights (10, 50, 85, and 120m) where meteorological measurements are taken; this way, correlation studies could be conducted. The mechanisms for insulator pollution and corrosion were discussed in chapter 2. In chapter 3, a detailed description was given of the test methodologies to determine the dust gauge pollution conductivity (in μS/cm) and corrosion rates (in μm/y).

The method of installing the dust gauges and corrosion specimens as well as their exposure durations are discussed below.

7.2.1 Dust gauges (DDG)

Figure 7.1 shows a dust gauge (DDG) installed on the weather mast at 10m and 120m above ground level. For insulator pollution severity measurements, a specially designed galvanised steel bracket was used to attach the dust gauges (DDG) to the weather tower, see Appendix D for detail.

Two dust gauges were attached to one bracket and oriented facing the prevailing direction north and south and another two dust gauges oriented facing east and west. An average monthly sampling duration of 30 days were used with the first samples taken in April 2002 and the last in October 2003, see Appendix F for detail.

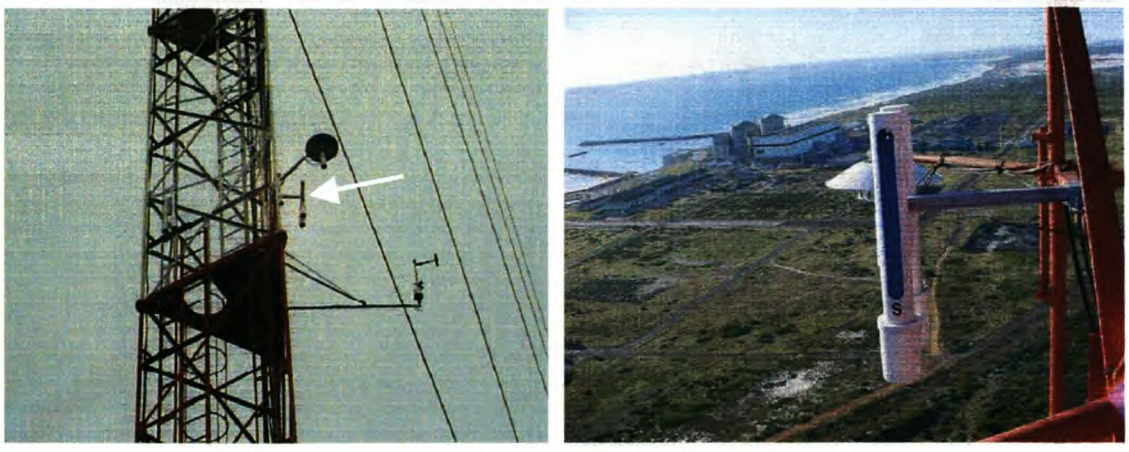

Fig. 7.1 Dust gauges installed at 10m and 120m above ground level using a galvanised steel bracket attached to the 120m high weather mast at the Koeberg Weather station.

7.2.2 Corrosion specimens

As explained in chapter 3 (section 3.2.2 and 3.2.3), corrosion tests were conducted using two methods: CLIMAT testing and metal specimens. The test specimens were attached to a fibreglass (nonconductive) bracket. The bracket in turn was attached to the weather mast at the prescribed heights and oriented facing a westerly direction (the direction of the sea, the marine pollution source), see figure 7.2.

Corrosion sampling was done somewhat different to the dust gauges; CLIMAT (wire-on-bolt) tests were conducted over a period of 98 days, while the metal coupons (flat metal specimens) were exposed to the atmosphere for 227 days. The first specimens were installed in March 2003 and the last specimens were removed in November 2003.

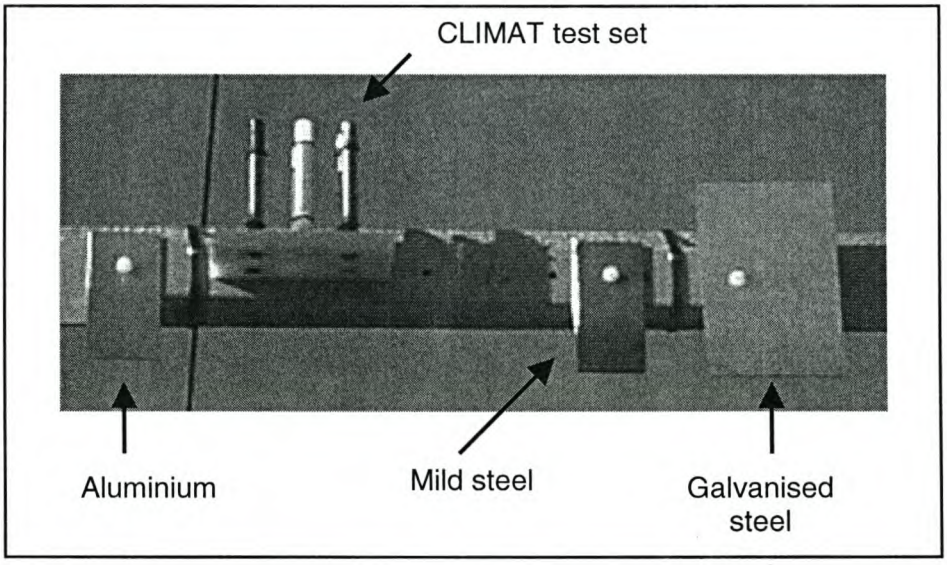

Fig. 7.2 Photo of a completed corrosion testing assembly showing the CLIMAT and flat metal specimens with the fibreglass bracket attached to the weather mast at the Koeberg Meteorological Station

7.3 HEIGHT-ABOVE-GROUND TEST RESULTS

Table 7.1 is a summary of the different types of atmospheric pollution tests that were performed at the corresponding heights on the 120m high weather mast at the Koeberg Weather station.

Pollution results from the dust gauge (DDG's) test method and the corrosion exposure tests are discussed below.

7.3.1 DDG test results

Table 7.1 show the minimum, maximum, and average pollution levels that were recorded at each test height. The same information is illustrated in the graph, see Figure 7.3; the monthly maximum index (see Table 6.1) was used to indicate the pollution classes [11]. Appendix F shows the detailed data; DDG pollution measurements and graphs for each test height on a month-to-month basis.

It can be seen from Figure 7.3 and Table 7.1 that all the test heights, with the exception of the 80m test height, have maximum pollution values in the very heavy pollution class, while the monthly average values are concentrated in very heavy pollution class (around 500 μS/cm).

NOTE: It was mentioned that the volume conductivity of the distilled water used for the measurements should not exceed 5 μS/cm (chapter 3, section3.1.1). However, due to limited availability of distilled water the volume conductivity exceeded 5 μS/cm in many instances (see Appendix F). This resulted in a measurement with a lower average conductivity value for the four directions.

7.3.1.1 DDG Probability plot: height-above-ground

Figure 7.4 shows the probability plot for maximum DDG conductivity values (µS/cm) in relation to height-above-ground level; taken on the 120m high weather mast at the Koeberg Weather station. It can be seen that there is a 50% probability that the DDG pollution level will be more than 1050 µS/cm (very heavy).

Repeating this exercise based on average DDG values, showed that there is a 50% probability that the DDG value will be more than 492 µS/cm (very heavy pollution class).

7.3.1.2 Effect of climatic conditions

The seasonal pattern for pollution levels is shown in Figure 7.5 for dust gauges installed on the 120 m high weather mast. The plot reflect that the first measurements were taken at the 10 m test height in April 2002, the 50 m DDG was installed a month later and the first measurement was taken in June 2002, the 85 m DDG was installed late in November 2002 and the first measurement taken in January 2003, while the 120 m DDG was installed in January 2003 and the first reading taken in March 2003.

Figure 7.6 illustrates the same information in conjunction with maximum monthly wind speed in m/s.

Dust gauge measurements

Appendix F reflects the detail of the dust gauge measurements. The dominant direction was pollution emanating from the west, followed by the east, south and north. Summers saw pollution from the west, east and south; while winters produced pollution from the north and east.

Table 7.1: DDG pollution levels and corrosion rates in relation to height-above-ground as recorded at the Koeberg Weather station

Height (m)	Dust gauge measurement results			Corrosion Test Results				
	DDG conductivity (µS/cm)			CLIMAT corrosion rate (µm/a)		Metal Coupons corrosion rate (µm/a)		
	Min	Max	Avg	Al-Fe	Al-Cu	Mild Fe	Galv Fe	Aluminium
120	193.69	957.18	453.70		—	14.33	1.1428	1.3382
	Medium	Very Heavy	Very Heavy		—	Low	Medium	High
80	60.31	746.12	342.87	33.79	—	15.19	1.4924	
	Light	Heavy	Heavy	Medium	—	Low	High	
50	207.25	1291	562.70		—	12.46	2.7055	
	Medium	Very Heavy	Very Heavy		—	Low	High	
10	117.29	1073.5	503.07		—	8.83	2.4072	1.4845
	Light	Very Heavy	Very Heavy		—	Low	High	High
3	No DDG measurements were taken at 3m above ground level			51.76	—	20.087	1.5816	
				High	—	Low	High	

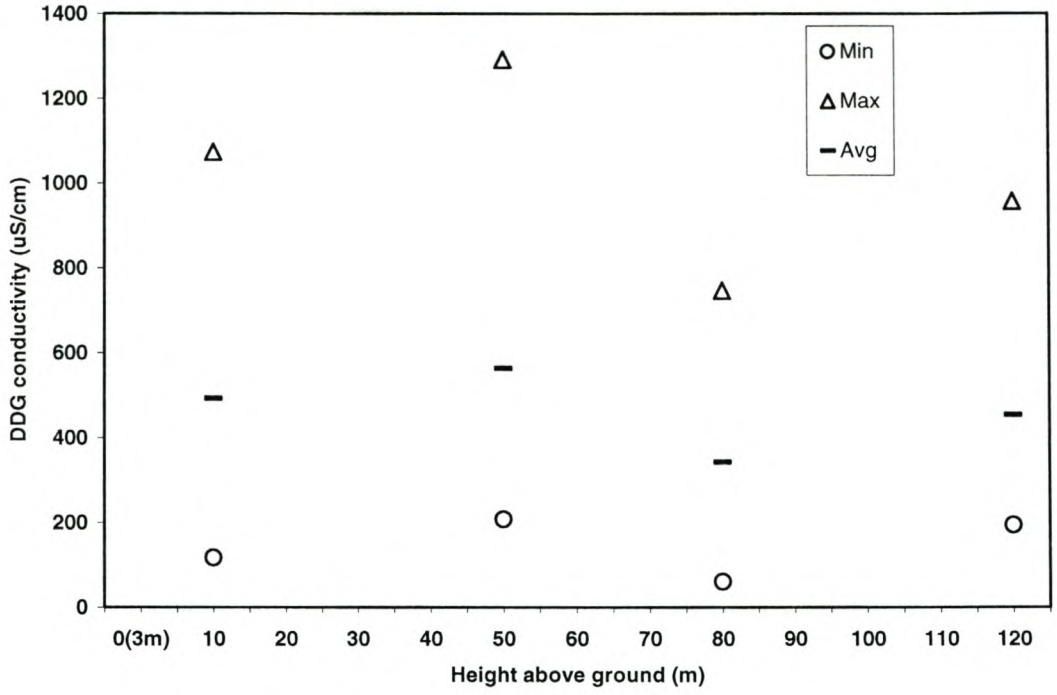

Fig. 7.3 DDG pollution levels at 10, 50, 80, and at 120m above ground level taken on the 120m high weather mast at the Koeberg Weather station.

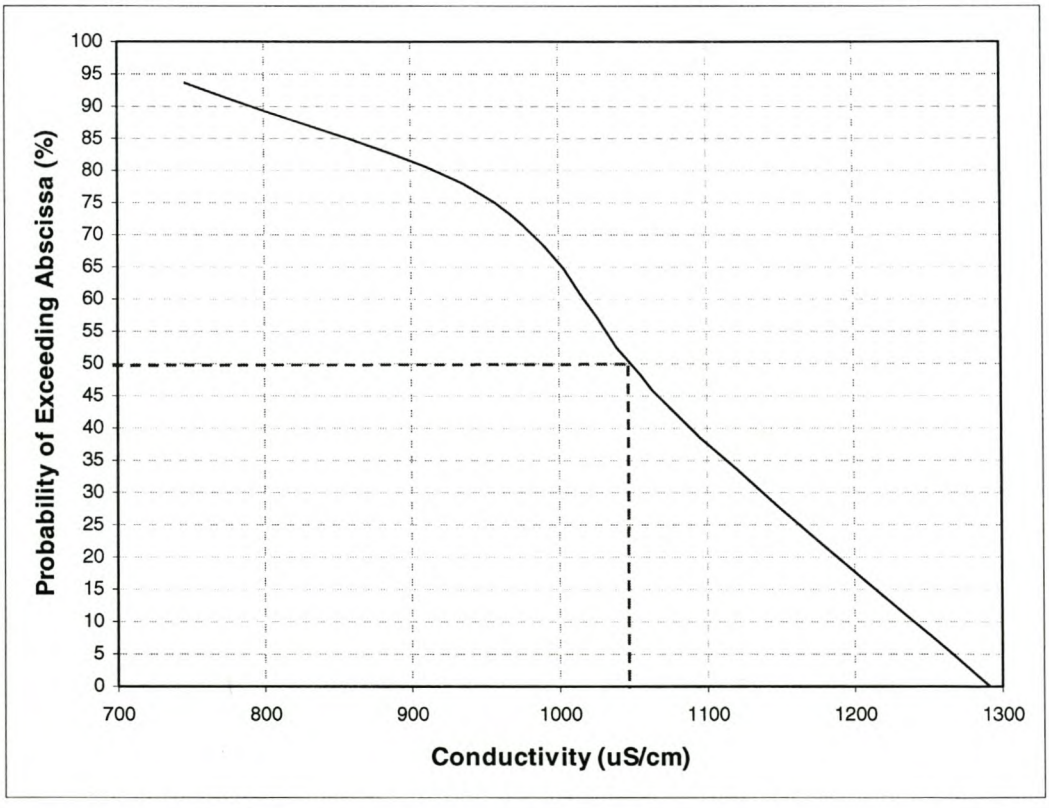

Fig. 7.4 Probability of DDG conductivity (maximum value) exceeding a certain value on the 120m high weather mast.

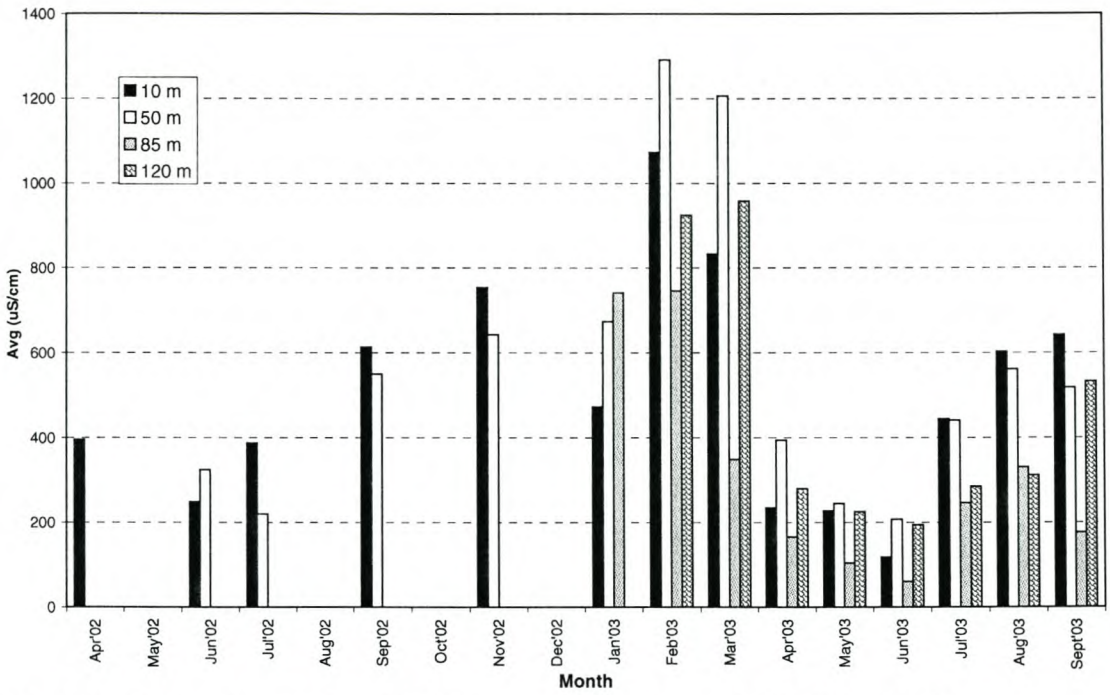

Fig. 7.5 Seasonal variation of DDG pollution levels at 10, 50, 80, and 120m above ground level taken on the 120 m high weather mast at the Koeberg Weather Station.

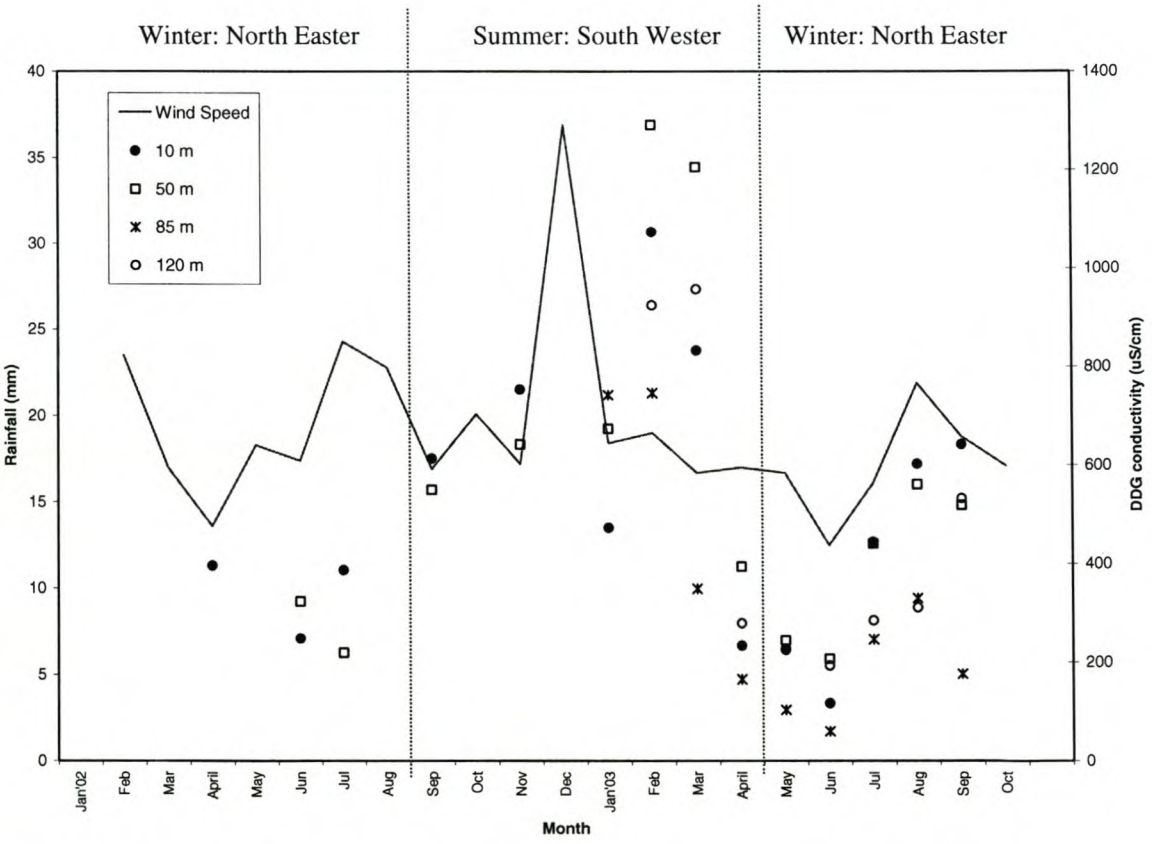

Fig. 7.6 Effect of seasonal variation in wind speed on DDG pollution levels at 10, 50, 80, and 120m above ground level.

7.3.2 Corrosion test results

Table 7.1 also include a summary of the corrosion test results as obtained over the monitoring period on the 120m high weather mast at the Koeberg Weather station. Figure 7.7 shows the metal specimen corrosion test results at various test heights along the 120m high weather mast for mild steel and galvanised steel. Appendix G provides more detailed data.

The test results from the CLIMAT and metal specimen test methods are discussed below.

7.3.2.1 CLIMAT test results

From Table 7.1 it can be seen that there were no CLIMAT results obtained for the aluminium-copper (Al-Cu) assembly at all test heights and for the aluminium-steel (Al-Fe) assembly at the 10, 50, and 120m test heights. The specimens at the above test heights could not be assessed since sections of the aluminium wire broke off, rendering the test invalid and a shorter duration of exposure is recommended for a retest [24]. No retesting was done, however, it is noted that a recommended exposure period of 90 days is too long for the Al-Cu assemblies; a more reasonable exposure period would be 30 to 50 days.

One point to note is the fact that no test results were obtained at any of the test heights for the CLIMAT (Al-Cu) assembly indicating that all test heights experience the same type of corrosion attack. The Al-Cu assembly has a very high galvanic ratio resulting in a faster corrosion rate when compared to the Al-Fe assembly (as discussed in chapter 6, section 6.2.3.2).

For the Al-Fe assembly the corrosion rates was high (C4) and medium (C3) for the 3m and 80m test heights respectively, indicative of a harsh and aggressive pollution environment.

7.3.2.2 Metal specimen corrosion test results

From Table 7.1 and Figure 7.7, it is can be seen that the corrosion class for the mild steel test low (C2) for all the test heights. This is a lower corrosivity index when compared to the other corrosion tests. A possible explanation is the fact that a decrease in corrosion rate for mild steel is experienced when a moisture film is formed on the metal surface (as explained in section 7.4.2). It should also be noted that only mechanical cleaning (with a non-metallic brush) was applied and more pollutants could have been removed if chemical cleaning would have been used as well, however, the test methods were limited to mechanical only.

The galvanised steel test results for all test heights up to 80 m above ground level produced corrosion rates in the high corrosion category; with the exception of the 120m test height which produced a medium corrosion level.

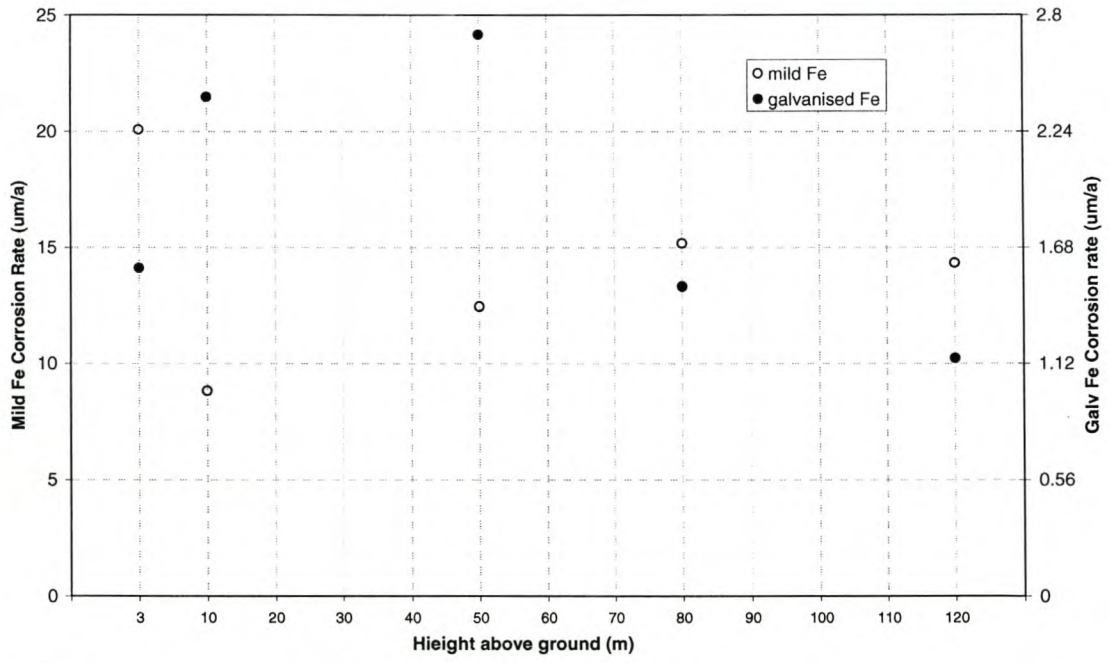

Fig. 7.7 Corrosion rates in relation to height-above-ground level (3, 10, 50, 80, 120m) as recorded on the 120m high mast at the Koeberg Weather Station.

7.4 SUMMARY

All test heights have more or less the same DDG conductivity values and corrosion rates, indicating that height does not really affect the pollution severity level.

7.4.1 Correlation studies

Table 7.2 is a summary of results from regression analysis for various parameters with the regression for all forced through the origin. A hypothesis test (t-test) was carried out to determine the usefulness of each relationship. A P-value smaller than 0.01 ($P < 0.01$) indicate that there is no useful relationship between the modelled parameters.

The best relationship (moderate negative linear) exists between maximum DDG pollution levels, height-above-ground level, and mild steel with an R^2 value of 0.62, see figure 7.8. Following close is the DDG and galvanised steel relationship with an R^2 value of 0.52 and a positive moderate linear relationship, see figure 7.9.

Table 7.2: Correlation parameters forced through the origin for test heights on the 120m high weather mast at the Koeberg Weather station.

Description		R^2	Standard Error	Slope, b	P-value
DDG vs Mild Fe	Avg	-0.3763	3.2825	0.02335	0.0248
	Max	-0.628	3.570	0.0105	0.0295
DDG vs Galv Fe	Avg	0.4098	0.6359	0.00421	0.02844
	Max	0.525859	0.570	0.0192	0.0227
Mild Fe vs Galv Fe		-0.414	0.973	0.1231	0.0915

Table 7.3: Correlation parameters not forced through the origin

Description		R^2	Standard Error	Slope, b	P-value
DDG vs Mild Fe	Avg	0.030258	3.8966	-0.00088	0.88869
	Max	0.0277	3.9016	-0.002751	0.8934
DDG vs Galv Fe	Avg	0.76318	0.5697	0.013089	0.32335
	Max	0.756829	0.577	0.00425	0.32829
Mild Fe vs Galv Fe		0.7476	0.5818	-0.50749	0.33505

Regression not forced through zero

The picture looks very different for the regression parameters not forced through zero, as shown in Table 7.3. Moderate positive linear relationships with R^2 values above 0.74 were produced for all relationships; with the exception of the DDG versus mild steel, which produced very weak positive linear relationships and R^2 values of less than 0.04.

The data for mild steel and galvanised steel is shown in Figure 7.10. The correlation produced a weak negative linear relationship, R^2 equal to 0.414. It appears that higher corrosion rates are recorded for the mild steel at higher altitude, with the reverse being true for the galvanised steel.

7.4.2 ISO corrosivity classification

The ISO corrosivity categories and corrosion rates for the mild steel and galvanised steel is given in Figure 7.11; with the mild steel producing results in the low (C2) category and galvanised steel in the medium (C3) and high (C4) categories. The variability in corrosion rate between the mild steel and galvanised steel can be explained as follows [79]:

The effect of temperature on atmospheric corrosion has not been the subject of many studies. It appears that the effect of temperature is greater on the atmospheric corrosion of carbon steel than on other metals. An increase in temperature accelerates corrosive attack by increasing the rate of electrochemical and chemical reactions and of the diffusion process. Consequently, under constant-humidity conditions, a temperature increase will promote corrosion.

Conversely, an increase in temperature can also cause a decrease in the corrosion rate by causing a more rapid evaporation of the surface moisture film. This reduces the time of wetness, which in turn, decreases the corrosion rate. In addition, as the temperature is increased, the solubility of oxygen and other corrosive gases in the moisture film is decreased.

The **mild steel corrosion rate decreases with the presence of a surface moisture film**, which is caused by a reduction in the time of wetness (TOW). The issue of concern is also the steel composition, as highlighted by King [79]; a question raised was the type of material to be used as a standard to test steel.

7.4.3 Linear Trendline analysis

Figure 7.12 indicate that there is a decrease in the maximum and average DDG pollution levels with an increase in height. From Figure 7.13 it is also evident that there is a decrease in galvanised steel and mild steel corrosion rates with an increase in height. The decrease in pollution levels is very evident at the 85m and 120m test heights.

The above finding is in contrast with findings from a study by Haberecht *et al* conducted in New Zealand of corrosion results over 10 years exposure and it was stated that, "there does not appear to be a strong relationship between rainfall, height above sea level, latitude and corrosion rate of zinc" [51].

To confirm the finding that pollution levels decrease with an increase in height, it is recommended that further height-above-ground pollution measurements be carried out, for a minimum of two years and, preferably at more than one site.

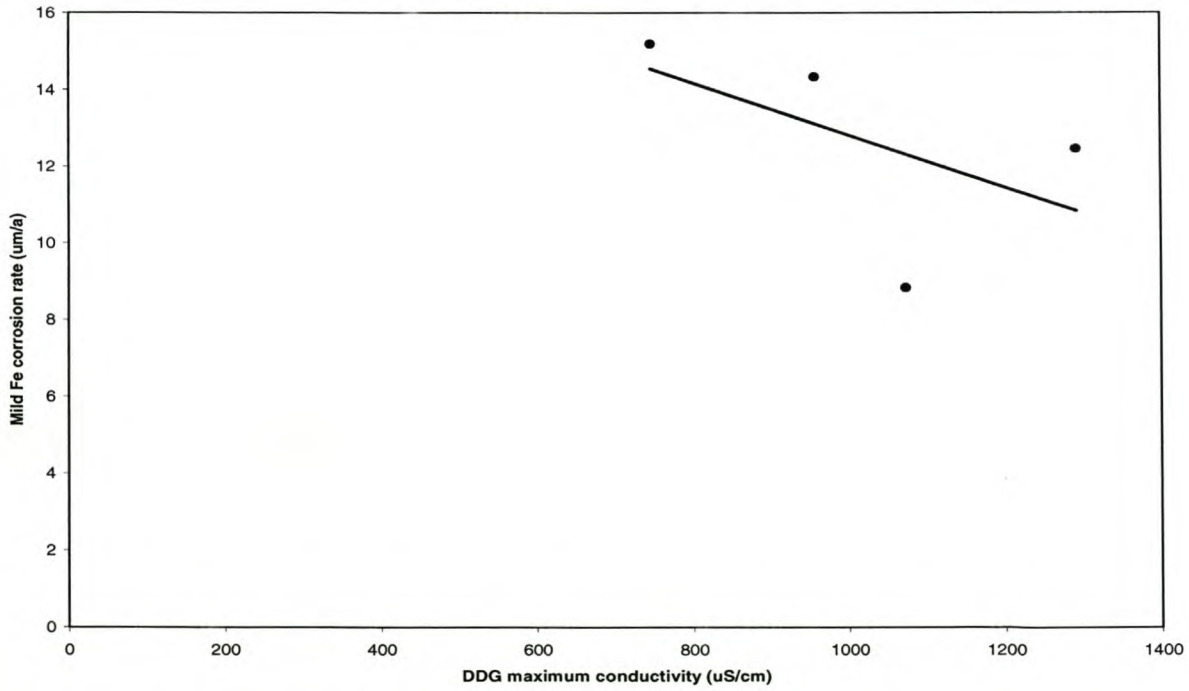

Fig. 7.8 Correlation between DDG (maximum) pollution values and mild steel corrosion rates recorded on the 120m high mast at the Koeberg Weather station (negative linear relationship).

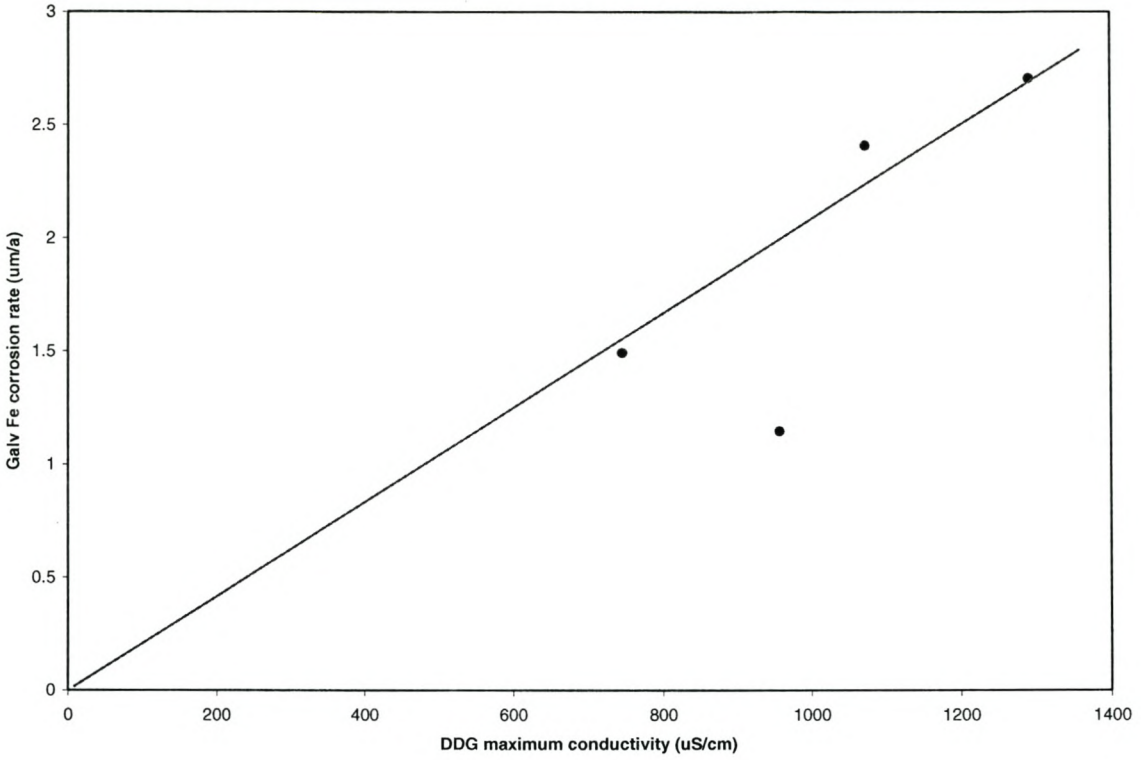

Fig. 7.9 Correlation between DDG (maximum) pollution values and galvanised steel corrosion rates (positive linear relationship).

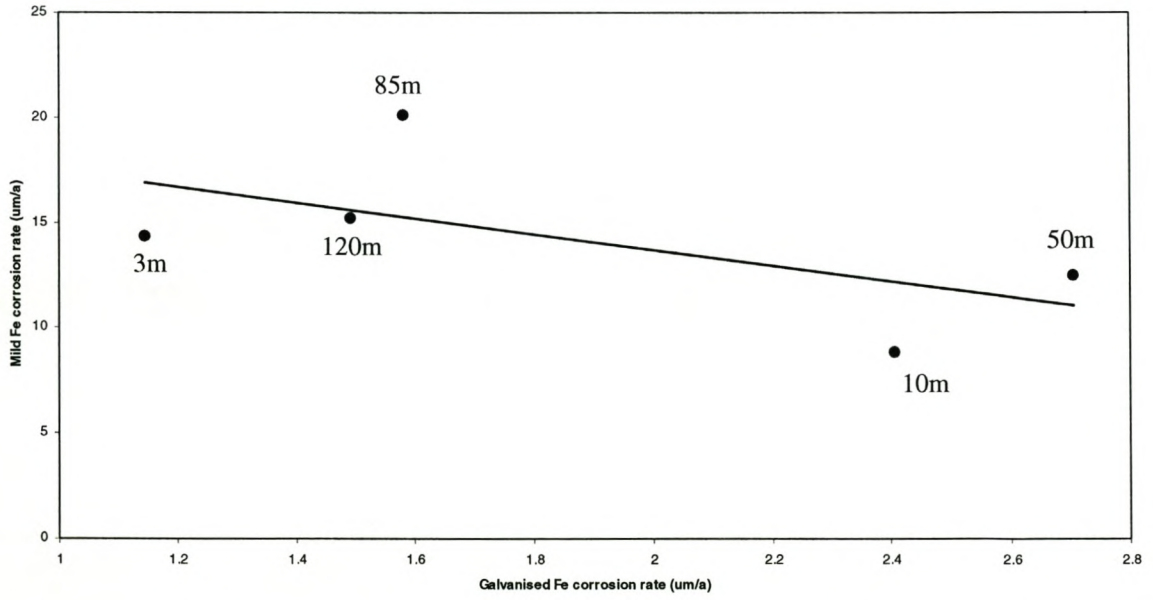

Fig. 7.10 Plot of corrosion rates for mild steel versus galvanised steel, together with test heights (negative linear relationship)

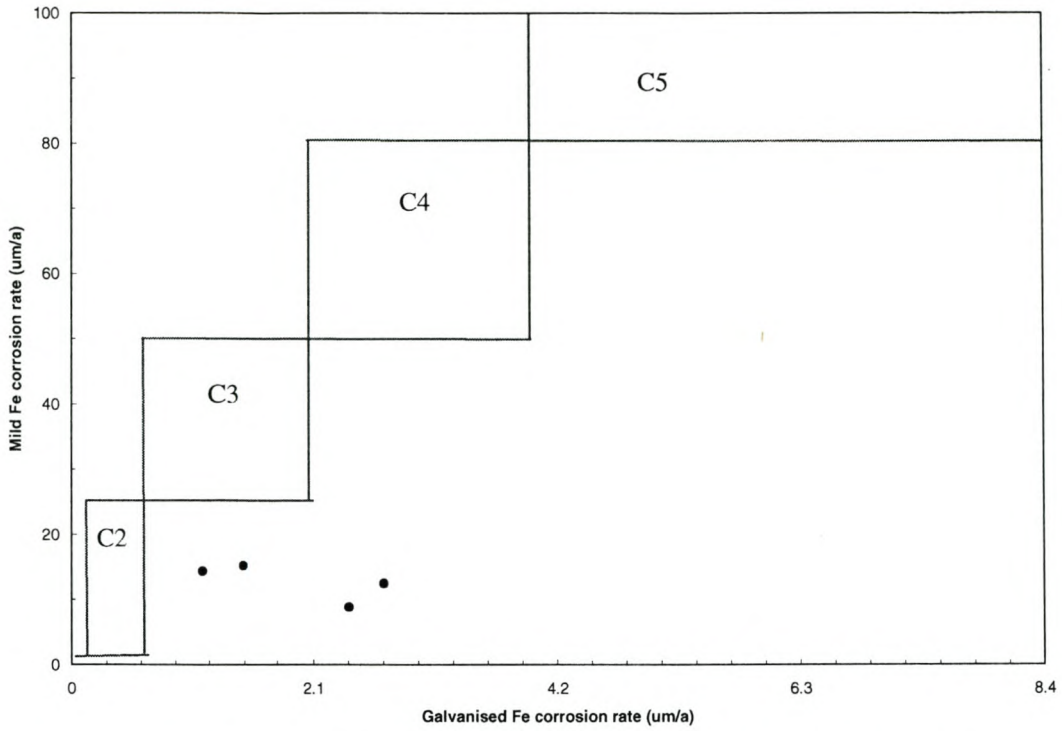

Fig. 7.11 Plot of corrosion rates for mild steel versus galvanised steel for test heights on the 120 m high weather mast at the Koeberg Meteorological station, together with ISO corrosivity categories.

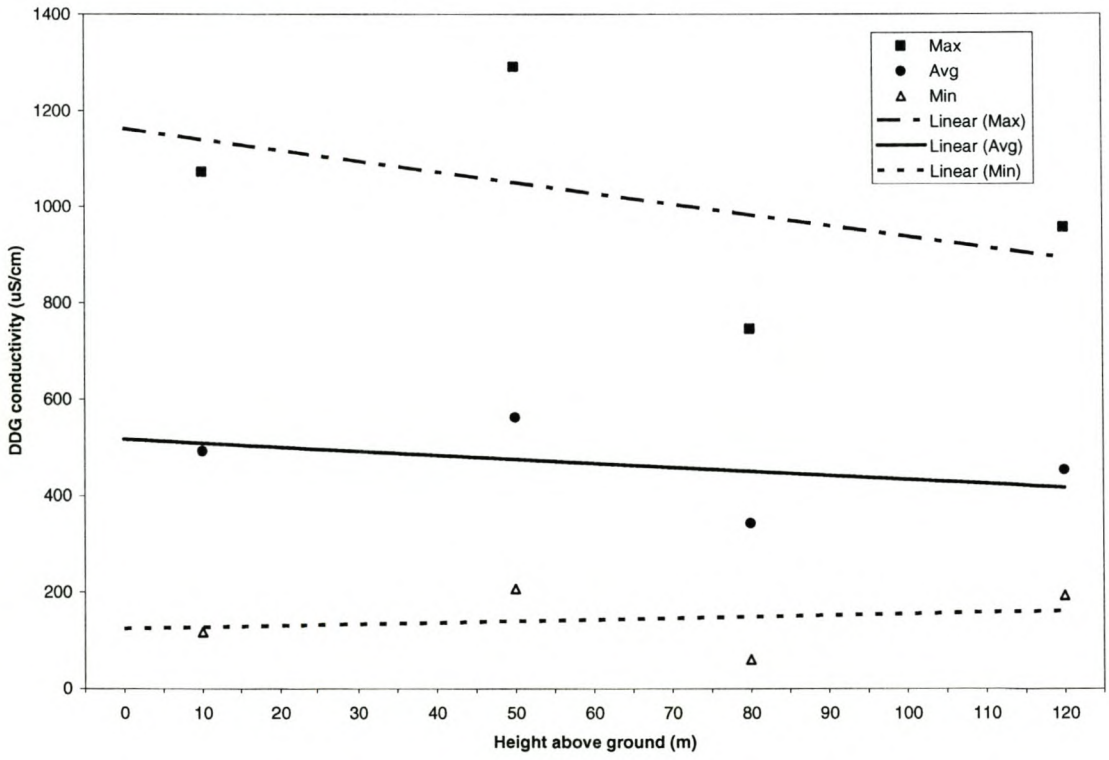

Fig. 7.12 Plot of DDG conductivity in relation to height above ground on the 120m high weather mast at the Koeberg Weather station, together with linear trendlines.

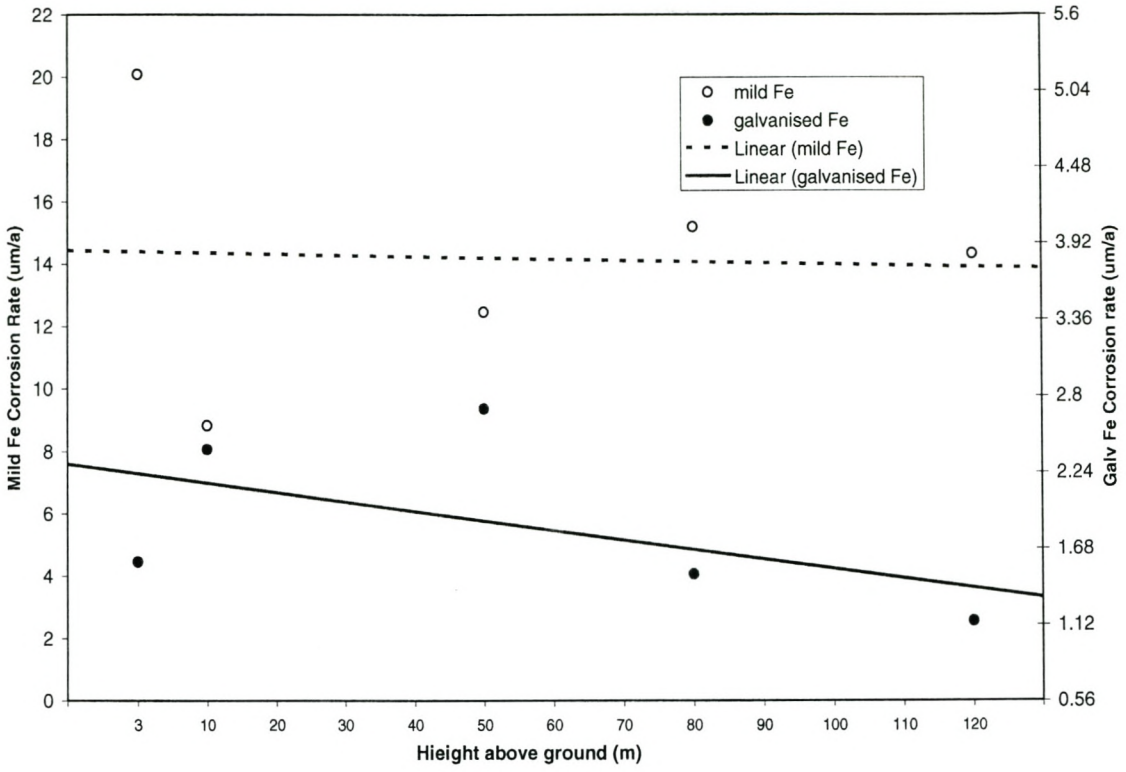

Fig. 7.13 Graph of corrosion rates for mild steel and galvanised steel in relation to height above ground recorded at the Koeberg Weather station, together trendlines.

7.5 CONCLUDING REMARKS

The height-above-ground study was conducted on the 120m high weather mast located at the Koeberg Weather station at five test heights, 3, 10, 50, 80, and 120m. DDG conductivity measurements and corrosion testing (CLIMAT and metals specimens) were utilised at each test height.

The maximum DDG conductivity values produced pollution severity levels ranging from very heavy to heavy on all the test heights. For the corrosion tests, the corrosivity indices varied between high (C4) and medium (C3); with the exception of the mild steel test, which produced low corrosion rates at all test heights. The pollution is indicative of a harsh and aggressive pollution environment – this is expected at a test site located 800m from the coast.

It was found that there is a decrease in pollution levels for the DDG and corrosion measurements with an increase in height. This trend, however, is very small (insignificant) and has no effect on the severity classification. This finding therefore further justifies the practice of mounting the dust gauges at a standard height of 3 metres while actual insulators could be at a height of, say, 8 to 40 metres above ground.

This finding (decrease in pollution with increase in height) is contrary to previous studies and it is recommended that further measurements be carried out to confirm the project findings.

A good correlation was developed between DDG pollution levels, height-above-ground, and mild steel corrosivity with an R^2 value of 0.62, and between DDG and galvanised steel producing an R^2 value of 0.52.

8

CONCLUSIONS AND RECOMMENDATIONS

The main objective of this research project was to develop a methodology which can be used to assist in developing an insulator pollution severity application map (INSMAP), more particularly for South Africa. The techniques must be able to assist in determining pollution severity levels.

At the inception of this project a phase one insulator pollution severity application map was available; this map was based on an existing corrosion map, climatic maps and dust gauge measurements. The phase one map was conservative and did not highlight localised pollution. The map consisted of all the Eskom technical service areas (TSAs) throughout South Africa with each TSA classified in terms of the highest pollution severity in that area. This approach was conservative and did not highlight localised pollution.

To confirm and possibly improve on this map, a phase two map was developed which was based on an electronic insulator pollution questionnaire survey. Feedback was obtained from 200 Eskom technical service areas (TSAs) throughout South Africa. The questionnaire was based on the IEC 60815 standard and with the use of an algorithm it can identify the insulator pollution severity level (or stress) and the existing insulation level (or strength) for a particular area. The phase two map was found to be unrealistic and there is gross exaggeration of the contamination levels for most of the TSAs when compared to results for the phase one map. In most instances the questionnaire was completed incorrectly by the Eskom field personnel – this is directly attributed to the lack of understanding by field personnel of environmental pollution and the impact on insulator performance. This fact was further evident in the answers provided for questions relating to the Climate Factor resulting in over-emphasis of this parameter in the questionnaire.

As a further development to confirm the findings of the phase one map, a phase three approach was followed, which was focused on an investigation into pollution measurement techniques and methodologies – this is the basis of this thesis. Based on the phase one map, a need was identified to confirm by measurements the impact of distance-to-coast. Also,

the validity of installing a dust gauge at 3 metres above ground level, while insulators are at a height of 8 to 40 meters, had to be investigated. Two environmental pollution monitoring programmes were established: a distance-to-coast study (to confirm the phase one map) and height-above-ground study (to confirm the dust gauge installation at 3 metres).

In order to correlate corrosion rates and insulator pollution measurements, and to confirm the validity of the phase one map based on a corrosion map, it was decided to include corrosion measurement tests. Various test methods are described with a complete testing procedure, descriptive equations and related pollution severity classifications for insulator pollution (DDG and ESDD) and corrosion (CLIMAT and metal specimens).

In order to come to a final conclusion, the aspirations for this project have to be re-stated. The project could be divided into three parts:

- **Phase 1:**

  The development of a preliminary version insulator pollution severity application map (IPSAM) based on a literature survey and an existing corrosion map. This was the foundation of this research study since this map already existed at the inception of this project. The methodology that was utilised to develop this map was investigated.

- **Phase 2:**

  The development of a insulator pollution map (IPSAM) based on a insulator pollution questionnaire survey. The methodology to develop this questionnaire was investigated.

- **Phase 3:**
  - Investigate pollution measurement techniques,
  - Develop a methodology to set up a typical test station,
  - Determine the effect of distance-to-coast on pollution severity levels by conducting pollution measurements at test sites along the coast,
  - Determine the effect of height-above-ground on pollution levels by conducting measurements at a test site.

The following was achieved:

- a detail literature study to identify the key criteria used during the development of the phase one map (IPSAM),
- an investigation of pollution measurement techniques,
- the development of an electronic insulator pollution severity questionnaire and a phase two IPSAM,
- setting up and obtaining data from a distance-to-coast test site,
- data analysis for the distance-to-coast study form test sites in the Western Cape (Cape Peninsula and along the West coast and South coast), and
- setting up and obtaining data from a height-above-ground test site.

The outputs of the above research are reported in Chapters 2 to 7. Concluding remarks are also given at the end of each chapter.

Conclusions

There were some important findings and achievements that emanated from the research. Some of these are highlighted below for the sake of completion and refreshment:

1. Two preliminary insulator pollution severity application maps were developed.
   The phase one map was based on a corrosion map and is a generalised representation of insulator pollution severity levels throughout South Africa.
   The phase two map was developed using an electronic questionnaire survey that was completed by field service personnel. The phase two map was found to be unrealistic and there is gross exaggeration of the contamination levels for most of the TSAs when compared to results from the phase one map. In most instances the questionnaire was completed incorrectly – this is directly attributed to the lack of understanding by field personnel of environmental pollution and the impact on insulator performance. This fact was further evident in the answers provided for questions relating to the Climate Factor resulting in over-emphasis of this parameter in the questionnaire (showing the need for proper training and a pollution measurement programme).
   The electronic insulator pollution questionnaire proved to be a very useful tool, however, the effective use of this tool is limited to a good understanding of insulator

pollution and the impact on performance. The tool assists with identifying atmospheric pollution sources, pollution severity levels, and insulation levels within a specific area.

2. It was shown that there is a good correlation between corrosion and insulator pollution flashover process. The main similarity is the presence of a conductive electrolyte to initiate the process. A major difference is the fact that corrosion requires no external voltage source to initiate the process, whereas the insulator pollution flashover process starts with the flow of leakage currents driven from a voltage source.

3. The complete testing procedure, descriptive equations and related pollution severity classifications are given for DDG, ESDD, and corrosion test methods (CLIMAT and metal specimens). The reader should be able to execute any of the abovementioned test protocols at a test site.

4. Criteria to determine the selection of a test site for atmospheric pollution monitoring was developed. Based on these criteria, the Koeberg-Muldersvlei 400kV line was selected for a detailed distance-to-coast atmospheric pollution regression study, and the 120m high weather mast located at the Koeberg Weather station was selected for the height-above-ground environmental pollution study.

5. The DDG and ESDD pollution tests produced very heavy pollution severity levels with an impact distance from the sea of 5 km and 800 m respectively. The difference in the test results is ascribed to the type of test method used; where the DDG test is a cumulative test also containing the maximum event, while the ESDD test is a snapshot with the likelihood of not capturing a maximum event due to natural washing. The corrosion rates for the CLIMAT (Al-Cu) test was very high for a distance of up to 1 km from the sea, while the impact distance was 50 m (KIPTS) for the flat metal specimen (galvanised steel) test for the very high corrosion category.

6. Corrosion rates and insulator pollution levels at the coast (KIPTS) were found to be 2 to 3 times higher than test sites located 800 m and further from the coast - mainly due to the high concentration of chloride (NaCl) and high relative humidity in this region.

7. The distance-to-coast study was conducted along the Koeberg-Muldersvlei 400 kV line and also included data from other test sites in the Cape Peninsula, and along the West and South Coast for a distance of up to 30 km from the coast. A very strong correlation was found between DDG pollution levels, distance from the coast, and mild steel corrosivity levels with an R^2 value of 0.75. A moderate linear relationship between DDG and ESDD pollution values were found with an R^2 value of 0.62.

8. The height-above-ground study was conducted on the 120m high weather mast located at the Koeberg Weather station at five test heights, 3, 10, 50, 80, and 120m. The DDG conductivity (maximum) values produced pollution severity levels ranging from very heavy to heavy for all test heights. For the corrosion tests (CLIMAT and metals specimens) the corrosivity indices varied between high (C4) and medium (C3). The exception was the mild steel test which produced low corrosion rates at all test heights; this is attributed to a moisture film which forms on the metal surface under high humidity conditions (close to coast) causing reduced corrosion activity.

9. It was found that there is a slight (insignificant) decrease in pollution levels for the DDG and corrosion tests with an increase in height – with no effect on the severity classification – therefore justifying the practice of mounting the dust gauges at a standard height of 3 metres while actual insulators could be at a height of, say, 8 to 40 metres above ground. A good correlation was developed between DDG pollution levels, height-above-ground, and mild steel corrosivity with an R^2 value of 0.62, and between DDG and galvanised steel producing an R^2 value of 0.52.

10. Various publications emanated from this research study [4], [5], [61], [81].

Recommendations

The following recommendations are given for further investigation and research:

1. It is recommended that further pollution measurements (marine, industrial, and agricultural) be conducted throughout South Africa and the results be collated into one pollution severity map for the country.

2. Further height-above-ground measurements are proposed to confirm the finding that there is a slight (insignificant) reduction in pollution levels with an increase in height.

This should preferably be carried out at more than one site to cover various pollution types.

3. Pollution monitoring test stations should be erected close to (or at) the major weather stations – thereby enabling correlations of pollution and weather data.

4. To set up a basic monitoring station the following could be incorporated:

Basic station:

- rain gauge (to indicate precipitation),
- dust gauge (for accumulated pollution and to capture a maximum event, indicate directionality and for chemical analysis),
- and corrosion test: CLIMAT (wire-on-bolt method) and/or metal specimens.

Additional

The following could be added:

- weather data (temperature, %RH, precipitation, UV solar radiation, wind speed, wind direction, wind run, rain),
- chloride concentration levels (salt candle method),

This type of test site would require monthly site visit to conduct dust gauge measurements and to replace the salt candle. The dust gauge captures the pollutants which can be used for further analysis (for example, chemical analysis) and the directionality feature identify critical wind directions and pollution sources

Advanced stations

At advanced test stations, the IPMR (Insulator Pollution Monitoring Relay) can be deployed to take pollution measurements at shorter intervals. By installing the IPMRs covering a good spatial spread of South Africa, the information can be fed into a central database and a dynamic insulator pollution severity application map (DIPSAM) can be made available after every download. The IPMR determines the pollution severity by measuring the surface conductivity on the test insulator. The test insulator is part of the IPMR unit.

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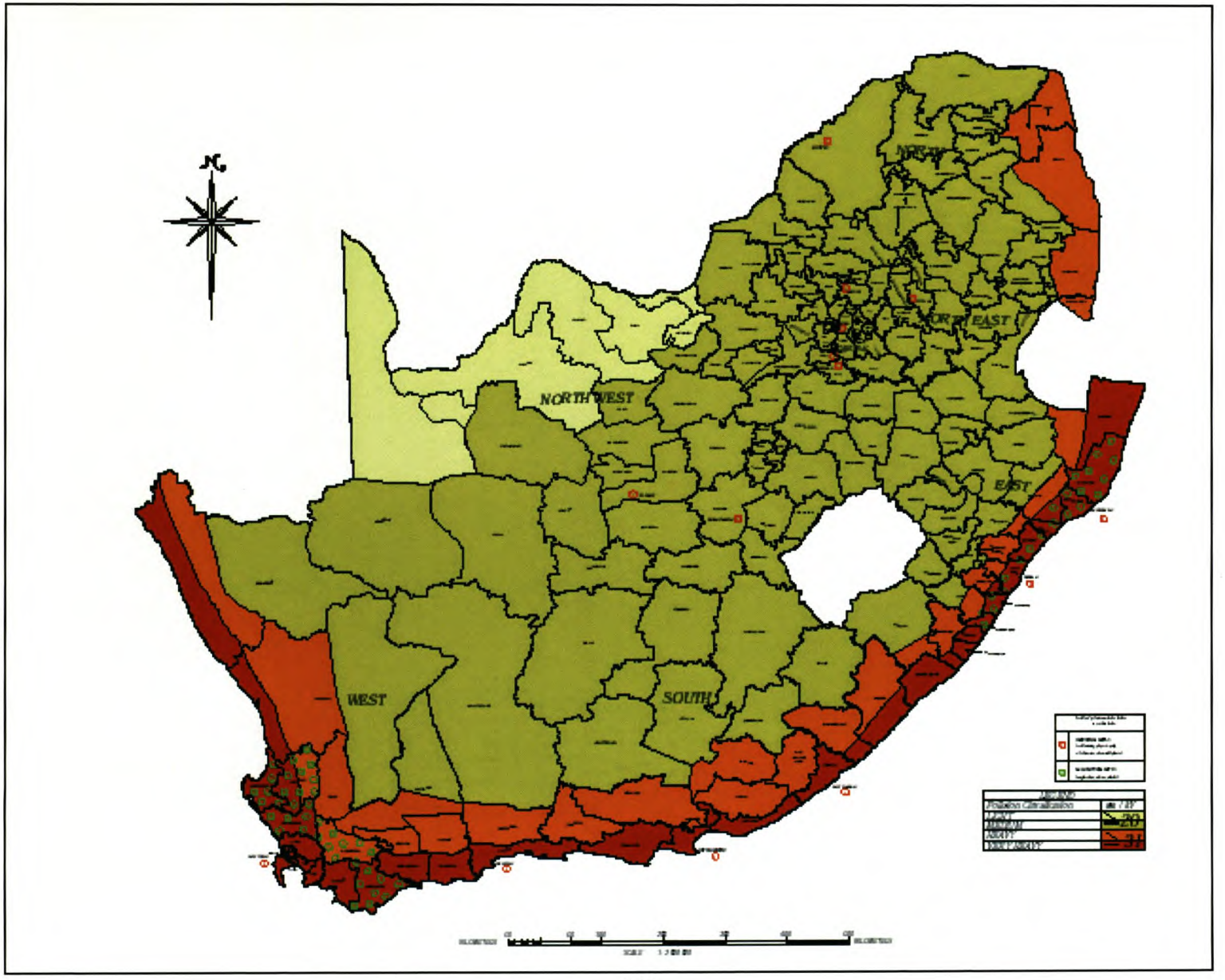
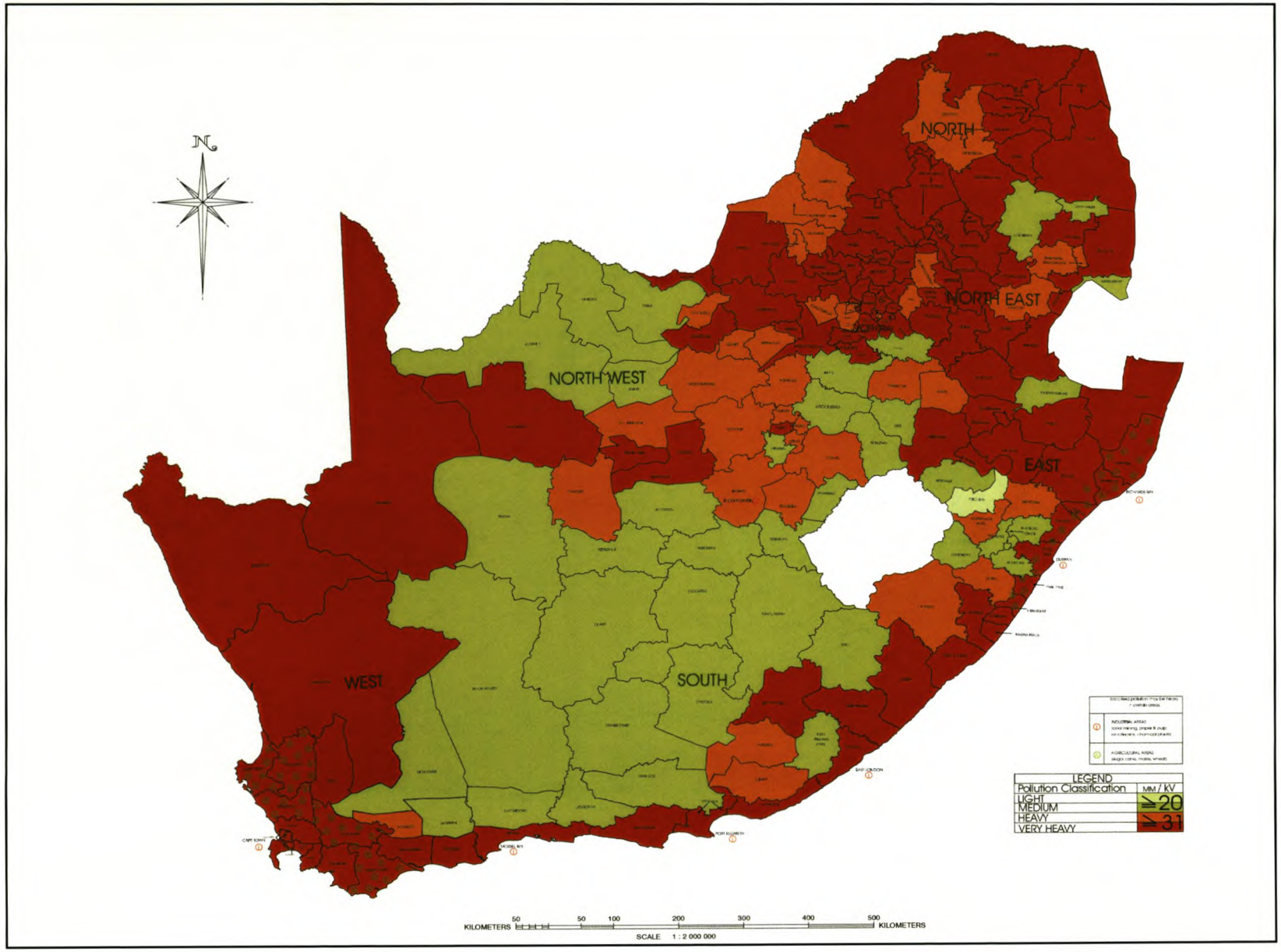
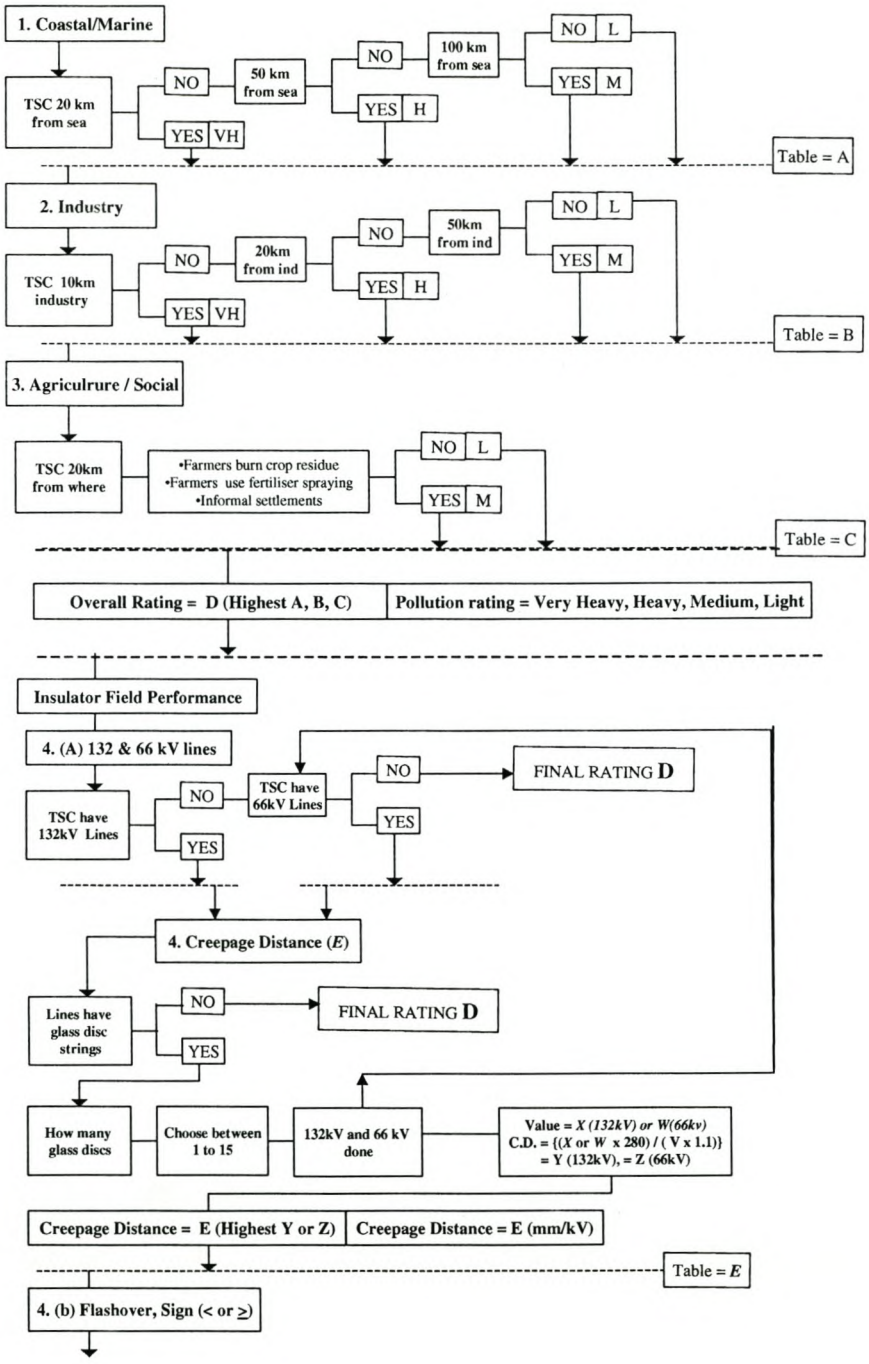
APPENDIX A: Phase One – Insulator Pollution Severity Application Map (IPSAM) for South Africa

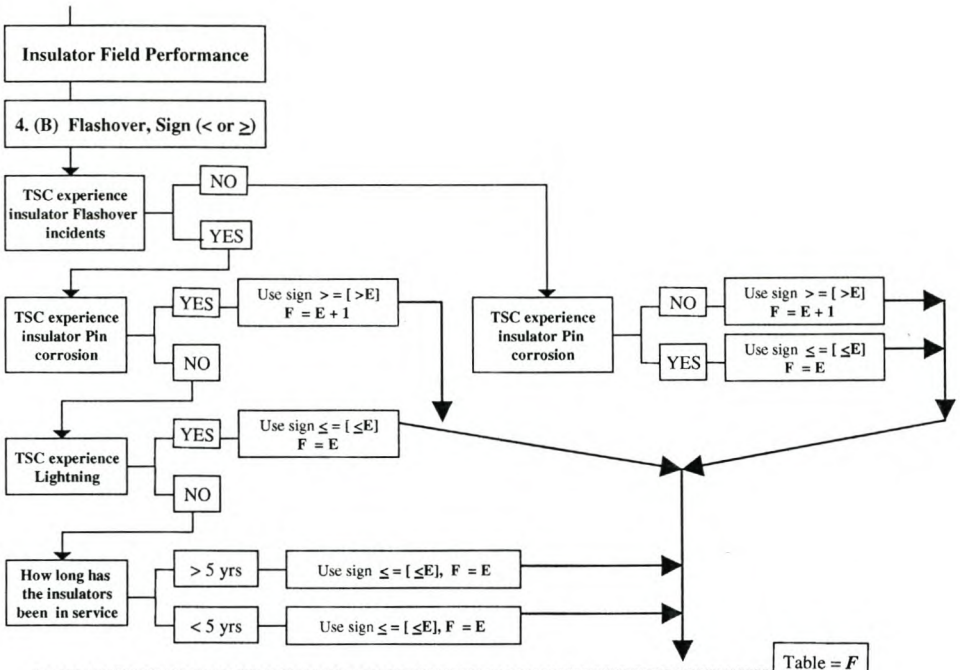


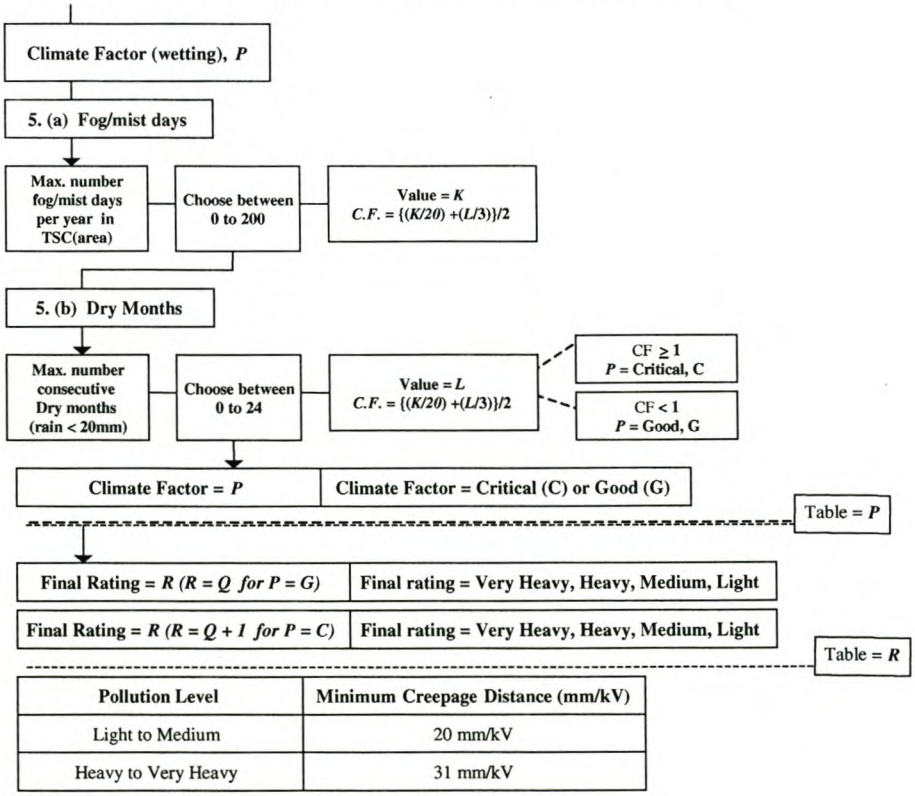
APPENDIX B: Phase Two – Insulator Pollution Severity Application Map (IPSAM) for South Africa





APPENDIX C: QUESTIONNAIRE FLOWCHART

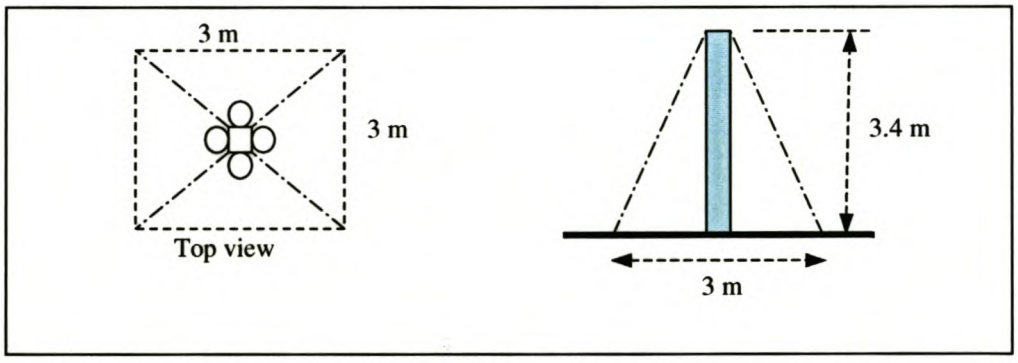




Pollution Level	Minimum Creepage Distance (mm/kV)
Light to Medium	20 mm/kV
Heavy to Very Heavy	31 mm/kV

D.1 **Distance from coast** monitoring: Directional dust deposit gauges (DDG)

Layout:



Support Column:	**Height: 3.4 metres** **Type: Mild Steel, H D Galvanised**
Adjustable Guys:	**Nylon Rope**
Dust Gauge:	**Collection Tubes** **Collection Jars**

Figure D.1 Dust gauge installation
(typical for distance-from-coast monitoring)

Figure D.2 Setting up GPS instrumentation (to determine test site locations)

Figure D.3 Sampling of dust gauges – Conductivity measurements

D.2 **Height above ground** monitoring: 120 m Weather Mast

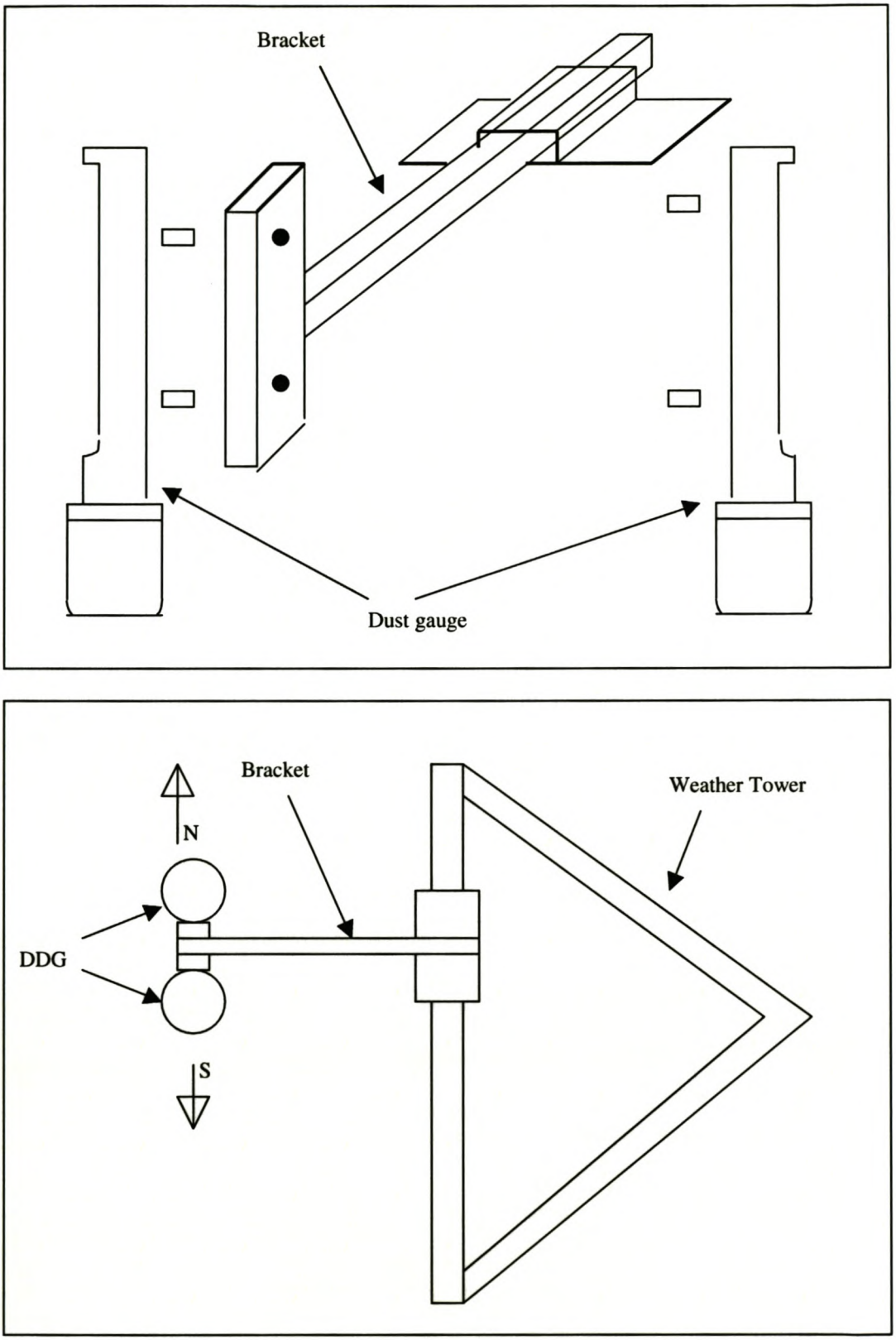


Figure D.4 Special bracket for DDG installation on weather mast
Assembly and orientation on tower (top view)

Fig D.5 Installing a dust gauge and an installed DDG on the weather mast at 10 m above ground

Fig D.6 Installed dust gauge on weather tower at 120m above ground

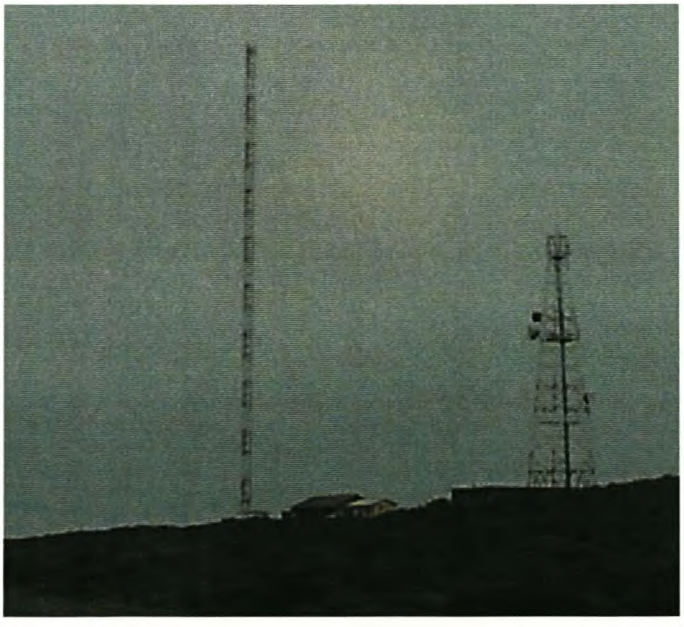


Fig D.7 120 m high weather mast to the left

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(1) **1 km test site** Date installed: 02 - 08 - 2001

DATE	RAIN METER (mm)	V_CNDd uS/cm	VOLUME_CONDUCTIVITY (uS/cm) NORTH	EAST	SOUTH	WEST	SOLUTION VOLUME (cm^3) NORTH	EAST	SOUTH	WEST	DAYS	NORM_CONDUCTIVIY (uS/cm) NORTH	EAST	SOUTH	WEST	AVG_C uS/cm	RATING
Sep'01		4.78	210	61.1	215	270	1000	500	500	800	46	267.67826	36.7304	137.1	276.751	179.565	W : N : S : E
Oct'01																	
Nov'01																	
Dec'01																	
Jan'02																	
Feb'02		2.41	217	107.1	399	226	500	500	500	500	161	39.985714	19.5075	73.8988	41.6627	43.764	S : W : N : E
Mar'02																	
Apr'02		3	62.6	47.8	91.9	111.1	500	500	500	500	45	39.733333	29.8667	59.2667	72.0667	50.233	W : S : N : E
May'02																	
Jun'02		3.77	308	330	131.1	158.2	500	500	500	500	58	157.36	168.74	65.8603	79.8776	117.959	E : N : W : S
Jul'02		3	258	411	220	169.7	500	500	500	1000	30	255	408	217	166.7	261.675	E : N : S : W
Aug'02																	
Sep'02		3	217	271	246	166	1000	500	500	1000	54	118.89	148.889	135	181.111	145.972	W : E : S : N
Oct'02																	
Nov'02		15.5	225	361	172	239	500	500	500	500	68	92.426471	152.426	69.0441	98.6029	103.125	E : W : N : S
Dec'02																	
Jan'03		4.43	159	363	242	150	500	500	500	500	73	63.521918	147.358	97.6315	59.8233	92.084	E : S : N : W
Feb'03		15.4	307	371	139	215	500	500	500	500	35	249.94286	304.8	105.943	171.086	207.943	E : N : W : S
Mar'03		35.4	245	205.4	122.5	176.2	500	500	500	500	28	224.57143	182.143	93.3214	150.857	162.723	N : E : W : S
Apr'03		10.11	118.3	195.9	126.5667	65.5	500	500	500	500	34	95.461765	163.932	102.756	48.8735	102.756	E : S : N : W
May'03		9.5	77.2	76.6	39.4	45.7	500	500	500	500	35	58.028571	57.5143	25.6286	31.0286	43.050	N : E : W : S
June'03		25.4	31.1	57.6	60	40	500	500	500	500	28	6.1071429	34.5	37.0714	15.6429	23.330	N : E : W : S
Aug'03		33.5	82.1	178	284	166.4	1000	1000	500	1000	65	44.861538	133.385	115.615	122.677	104.135	E : W : S : N
Sep'03		45.8	98.3	183.4	124.2	116	500	500	500	500	34	46.323529	121.412	69.1765	61.9412	74.713	E : S : W : N

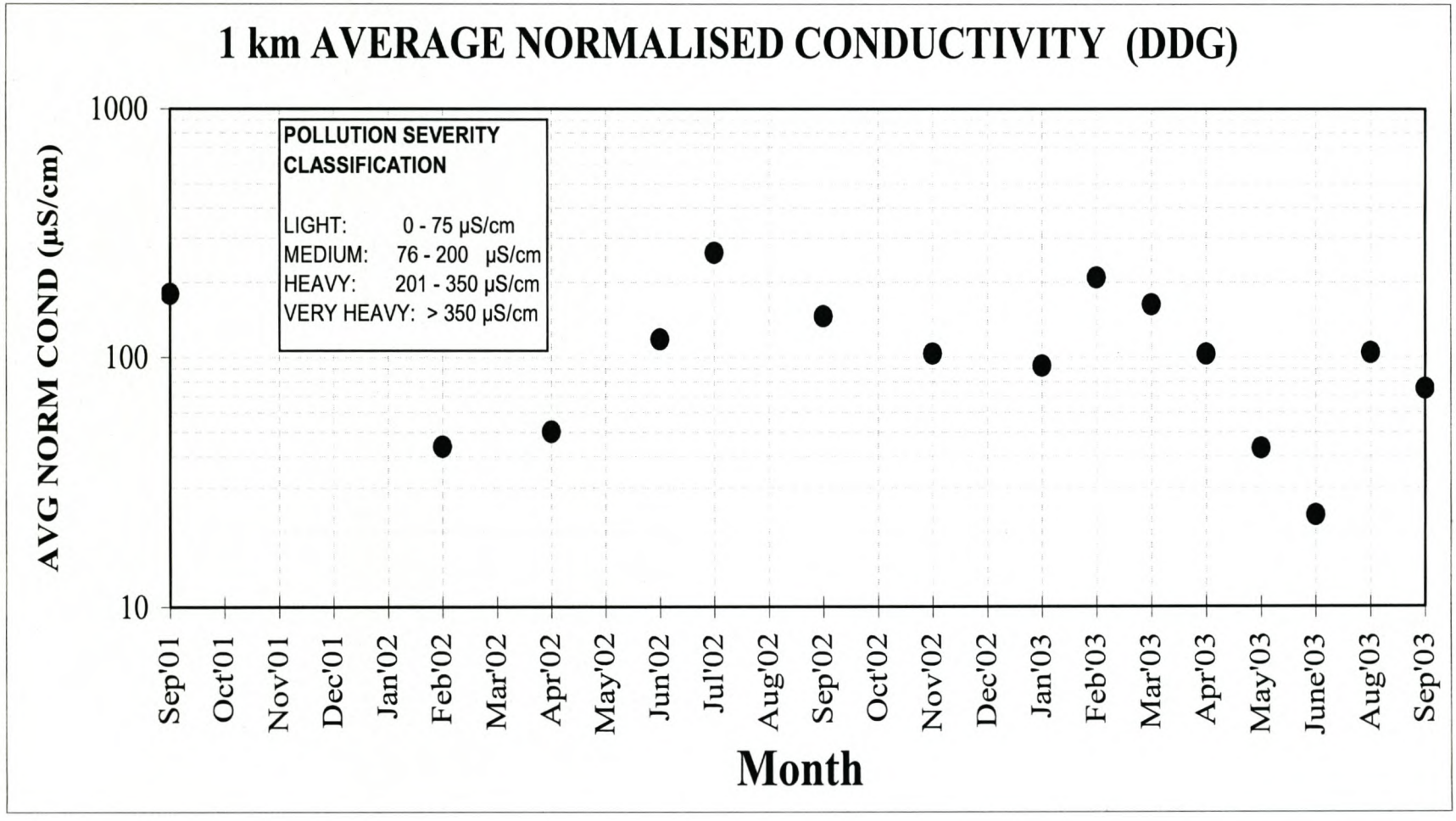


Fig. E.1 Plot of DDG measurements at the 1 km test site along the Koeberg – Muldersvlei 400 kV line

(2) **2 km test site** Date installed: 02 - 08 - 2001

DATE	RAIN METER (mm)	V_CNDd uS/cm	VOLUME_CONDUCTIVITY (uS/cm) NORTH	EAST	SOUTH	WEST	SOLUTION VOLUME (cm^3) NORTH	EAST	SOUTH	WEST	DAYS	NORM_CONDUCTIVIY (uS/cm) NORTH	EAST	SOUTH	WEST	AVG_C uS/cm	RATING
Sep'01		4.78	109.1	87.8	61.9	217	800	500	500	800	46	68.034783	54.1435	37.2522	138.404	74.459	W : N : E : S
Oct'01																	
Nov'01																	
Dec'01																	
Jan'02																	
Feb'02																	
Mar'02																	
Apr'02		3	99.3	186	114.2	86	500	500	500	500	206	14.024272	26.6505	16.1942	12.0874	17.239	E : S : N : W
May'02																	
Jun'02		3.77	138.9	284	114.1	147	500	500	500	500	58	69.894828	144.947	57.0672	74.0845	86.498	E : W : N : S
Jul'02		3	83.4	253	117.4	139.3	500	500	500	500	30	80.4	250	114.4	136.3	145.275	E : W : S : N
Aug'02																	
Sep'02		3	147	358	161	195	1000	1000	500	1000	54	80	197.222	87.7778	106.667	117.917	E : W : S : N
Oct'02																	
Nov'02		15.5	221	376	316	173	500	500	500	500	68	90.661765	159.044	132.574	69.4853	112.941	E : S : N : W
Dec'02																	
Jan'03		4.43	247	254	195	197	500	500	500	500	73	99.686301	102.563	78.3164	79.1384	89.926	E : N : W : S
Feb'03		15.4	142	236	181	68.5	500	500	500	500	35	108.51429	189.086	141.943	45.5143	121.264	E : S : N : W
Mar'03		8.2	100.6	237.3	139.1	91.2	500	500	500	500	28	99	245.464	140.25	88.9286	143.411	E : S : N : W
Apr'03		2.92	44.4	136.2	109.1	40.3	500	500	500	500	34	36.6	117.6	93.6882	32.9824	70.218	E : S : N : W
May'03		7.34	37.8	108.9	50.3	41.4	500	500	500	500	35	26.108571	87.0514	36.8229	29.1943	44.794	E : S : W : N
June'03		6.8	17.92	70.2	55.3	13.2	500	500	500	500	28	11.914286	67.9286	51.9643	6.85714	34.666	E : S : N : W
Aug'03		43.9	71.5	149	472	201	1000	1000	500	1000	65	25.476923	97.0154	197.585	145.015	116.273	S : W : E : N
Sep'03		63.7	97.2	156.4	197.2	101.2	500	500	500	500	34	29.558824	81.7941	117.794	33.0882	65.559	S : E : W : N

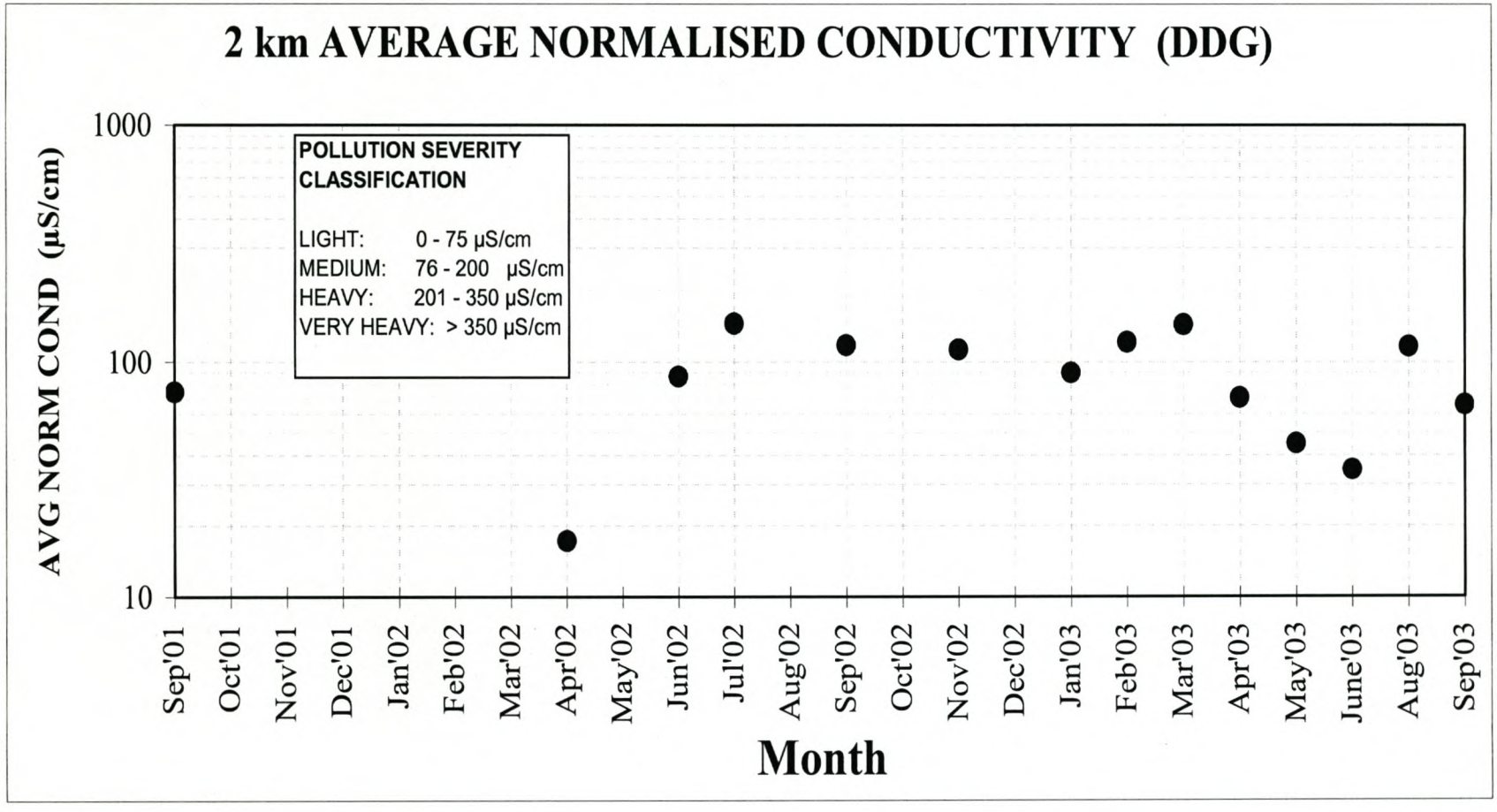


Fig. E.2 Plot of DDG measurements at the 2 km test site along the Koeberg – Muldersvlei 400 kV line

(3) **3 km test site** Date installed: 02 - 08 - 2001

DATE	RAIN METER (mm)	V_CNDd uS/cm	VOLUME_CONDUCTIVITY (uS/cm) NORTH	EAST	SOUTH	WEST	SOLUTION VOLUME (cm^3) NORTH	EAST	SOUTH	WEST	DAYS	NORM_CONDUCTIVIY (uS/cm) NORTH	EAST	SOUTH	WEST	AVG_C uS/cm	RATING
Sep'01		4.78	150.1	321	214	186.9	500	500	500	1000	46	94.773913	206.23	136.448	118.774	139.057	E : S : W : N
Oct'01																	
Nov'01																	
Dec'01																	
Jan'02																	
Feb'02																	
Mar'02																	
Apr'02		3	565	671	544	532	500	500	500	500	210	80.285714	95.4286	77.2857	75.5714	82.143	E : N : S : W
May'02																	
Jun'02		3.77	117.5	214	258	211	500	500	500	500	58	58.825862	108.74	131.498	107.188	101.563	S : E : W : N
Jul'02																	
Aug'02																	
Sep'02		3	187	641	307	219	500	500	500	500	98	56.326531	195.306	93.0612	66.1224	102.704	E : S : W : N
Oct'02																	
Nov'02		15.5	133	393	343	454	500	500	500	500	61	57.786885	185.656	161.066	215.656	155.041	W : E : S : N
Dec'02																	
Jan'03		4.43	511	728	134	269	500	500	500	500	73	208.17945	297.358	53.2479	108.727	166.878	E : N : W : S
Feb'03		15.4	162.5	285	163.4	189.5	500	500	500	500	35	126.08571	231.086	126.857	149.229	158.314	E : W : S : N
Mar'03		14.3	458	295	184.1	307	500	500	500	500	28	475.39286	300.75	181.929	313.607	317.920	N : W : E : S
Apr'03		10.1	119	203	115.5	120.8	500	500	500	500	35	93.342857	165.343	90.3429	94.8857	110.979	E : W : N : S
May'03		6.44	136	65.5	95.7	106	500	500	500	500	34	114.31765	52.1118	78.7588	87.8471	83.259	N : W : S : E
June'03		14.79	64.7	130.8	60.4	163.4	500	500	500	500	28	53.475	124.296	48.8679	159.225	96.466	W : E : N : S
Aug'03		22.2	105.61	138.4	183	123.7	1000	500	500	1000	65	76.993846	53.6308	74.2154	93.6923	74.633	W : N : S : E
Sep'03		48.3	132.5	173.5	142.2	99.8	500	500	500	500	34	74.294118	110.471	82.8529	45.4412	78.265	E : S : N : W

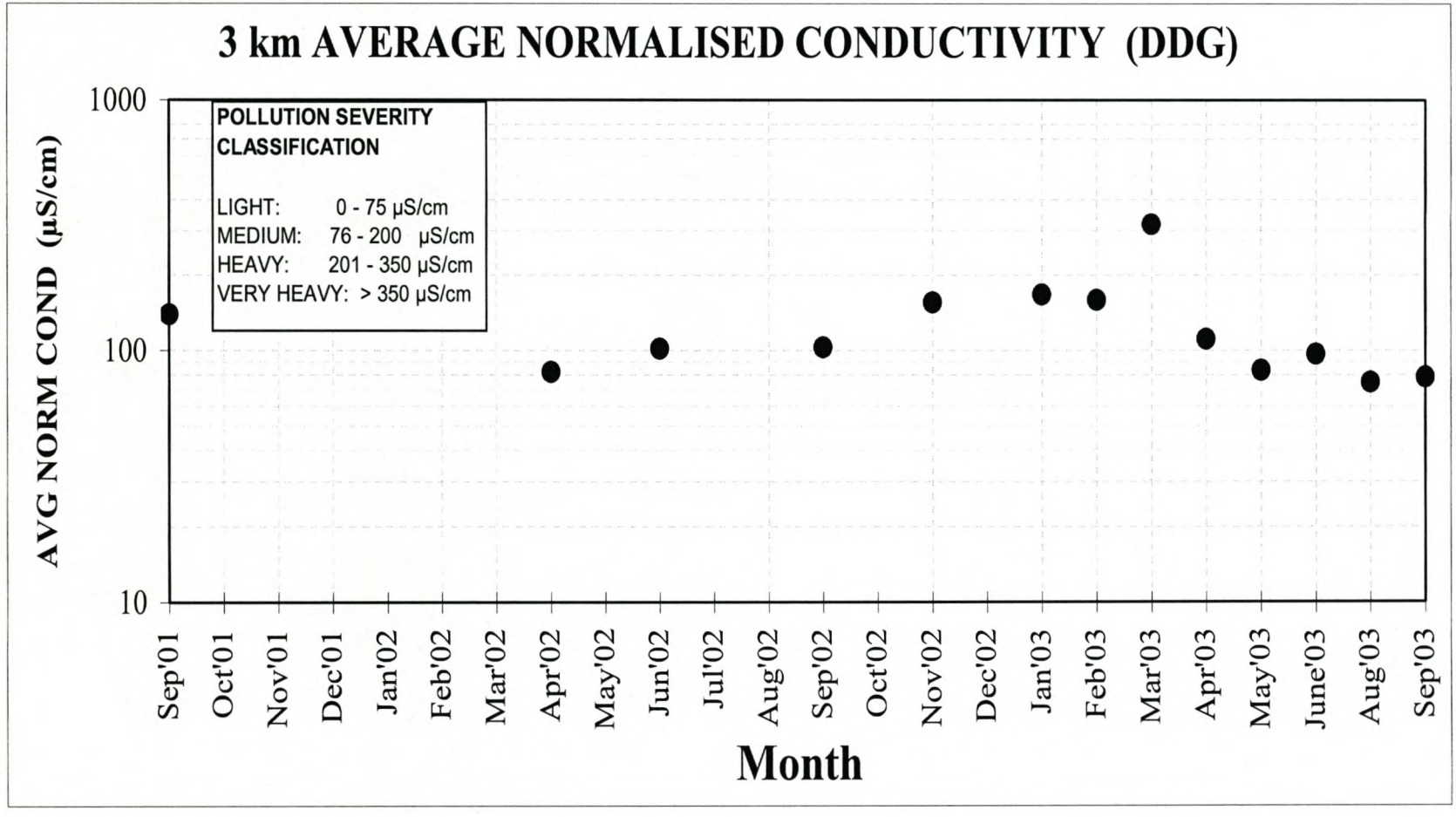


Fig. E.3 Plot of DDG measurements at the 3 km test site along the Koeberg – Muldersvlei 400 kV line

(4) **4 km test site** Date installed: 12 - 06 - 2002

DATE	RAIN METER (mm)	V_CNDd uS/cm	VOLUME_CONDUCTIVITY (uS/cm) NORTH	EAST	SOUTH	WEST	SOLUTION VOLUME (cm^3) NORTH	EAST	SOUTH	WEST	DAYS	NORM_CONDUCTIVIY (uS/cm) NORTH	EAST	SOUTH	WEST	AVG_C uS/cm	RATING
Jul'02		3	27.8	52.6	45.3	28.7	500	500	500	500	37	20.10810811	40.2162	34.2973	20.8378	28.865	E : S : W : N
Aug'02																	
Sep'02		3	36.9	37.9	42.5	29.2	500	500	500	500	54	18.83333333	19.3889	21.9444	14.5556	18.681	S : E : N : W
Oct'02																	
Nov'02		15.5	59.3	24.6	124.6	45.1	500	500	500	500	63	20.85714286	4.33333	51.9524	68	36.286	S : W : N : E
Dec'02																	
Jan'03		4.43	61.7	95.6	84.1	33.7	500	500	500	500	78	22.02692308	35.0654	30.6423	11.2577	24.748	E : S : N : W
Feb'03		15.4	43.2	74.4	102.2	91.2	500	500	500	500	35	23.82857143	50.5714	74.4	64.9714	53.443	S : W : E : N
Mar'03		4.8	306	47.7	293.3	217	500	500	500	500	28	322.7142857	45.9643	309.107	227.357	226.286	N : S : W : E
Apr'03		5.3	173.5	36.5	182.1	147.1	500	500	500	500	35	144.1714286	26.7429	151.543	121.543	111.000	S : N : W : E
May'03		3.47	88.8	24.9	81.3	91.5	500	500	1000	600	34	75.29117647	18.9088	137.347	93.2082	81.189	S : W : N : E
Jun'03		15.6	88.6	27.3	82.5	86.3	500	500	500	500	28	78.21428571	12.5357	71.6786	75.75	59.545	N : W : S : E
Aug'03		23.7	122.4	228	138.3	112.5	1000	500	1000	1000	65	91.10769231	94.2923	105.785	81.9692	93.288	S : E : N : W
Sep'03		43.8	153.2	131.1	119.3	107.4	500	500	1000	1000	34	96.52941176	77.0294	133.235	112.235	104.757	S : W : N : E

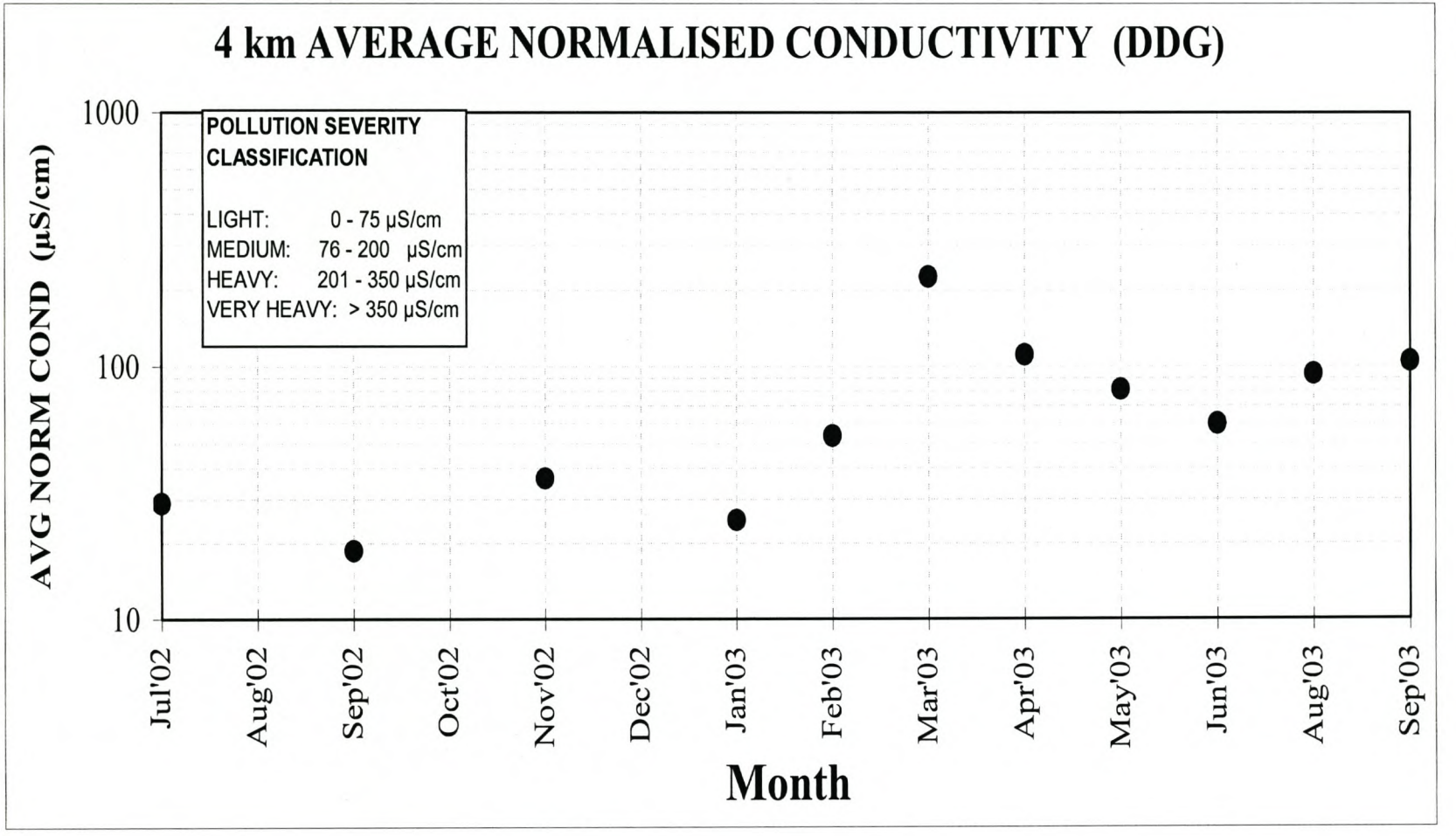


Fig. E.4 Plot of DDG measurements at the 4 km test site along the Koeberg – Muldersvlei 400 kV line

(5) **5 km test site** Date installed: 29 - 07 - 2002

DATE	RAIN METER (mm)	V_CNDd uS/cm	VOLUME_CONDUCTIVITY (uS/cm) NORTH	EAST	SOUTH	WEST	SOLUTION VOLUME (cm^3) NORTH	EAST	SOUTH	WEST	DAYS	NORM_CONDUCTIVIY (uS/cm) NORTH	EAST	SOUTH	WEST	AVG_C uS/cm	RATING
Sep'02		3	315	180	157.5	210	1000	500	500	500	44	212.727	120.682	105.341	141.136	144.972	N: W : E : S
Oct'02																	
Nov'02		15.5	410	383	578	309	1000	1000	500	500	63	187.857	175	267.857	139.762	192.619	S : N : E : W
Dec'02																	
Jan'03		4.43	126.6	93.9	295	194.6	500	500	500	500	79	46.394	33.9759	110.343	72.2165	65.732	S : W : N : E
Feb'03		15.4	357.06667	329	396	346.2	500	500	500	500	34	301.471	276.706	335.824	291.882	301.471	S : N : W : E
Mar'03		3.5	202	498	427	316	1000	500	500	1000	28	425.357	529.821	453.75	669.643	519.643	W : E : S : N
Apr'03		5.36	233	324	385	125	1000	500	500	500	35	390.240	273.12	325.406	102.549	272.829	N : S : E : W
May'03		2.07	152.3	143.4	196.2	154.4	1000	500	1000	500	35	257.537	121.14	332.794	130.569	210.510	S : N : W : E
June'03		3.1	135.5	92.5	111.3	56.7	500	500	500	500	27	147.111	99.3333	120.222	59.5556	106.556	N : S : E : W
Aug'03		30	86.8	164.7	177.3	99.8	1000	1000	1000	1000	56	60.857	144.321	157.821	74.7857	109.446	S : E : W : N
Sep'03		14.6	137.4	210	216	120.7	1000	500	500	1000	43	171.349	136.326	140.512	148.047	149.058	N : W : S : E

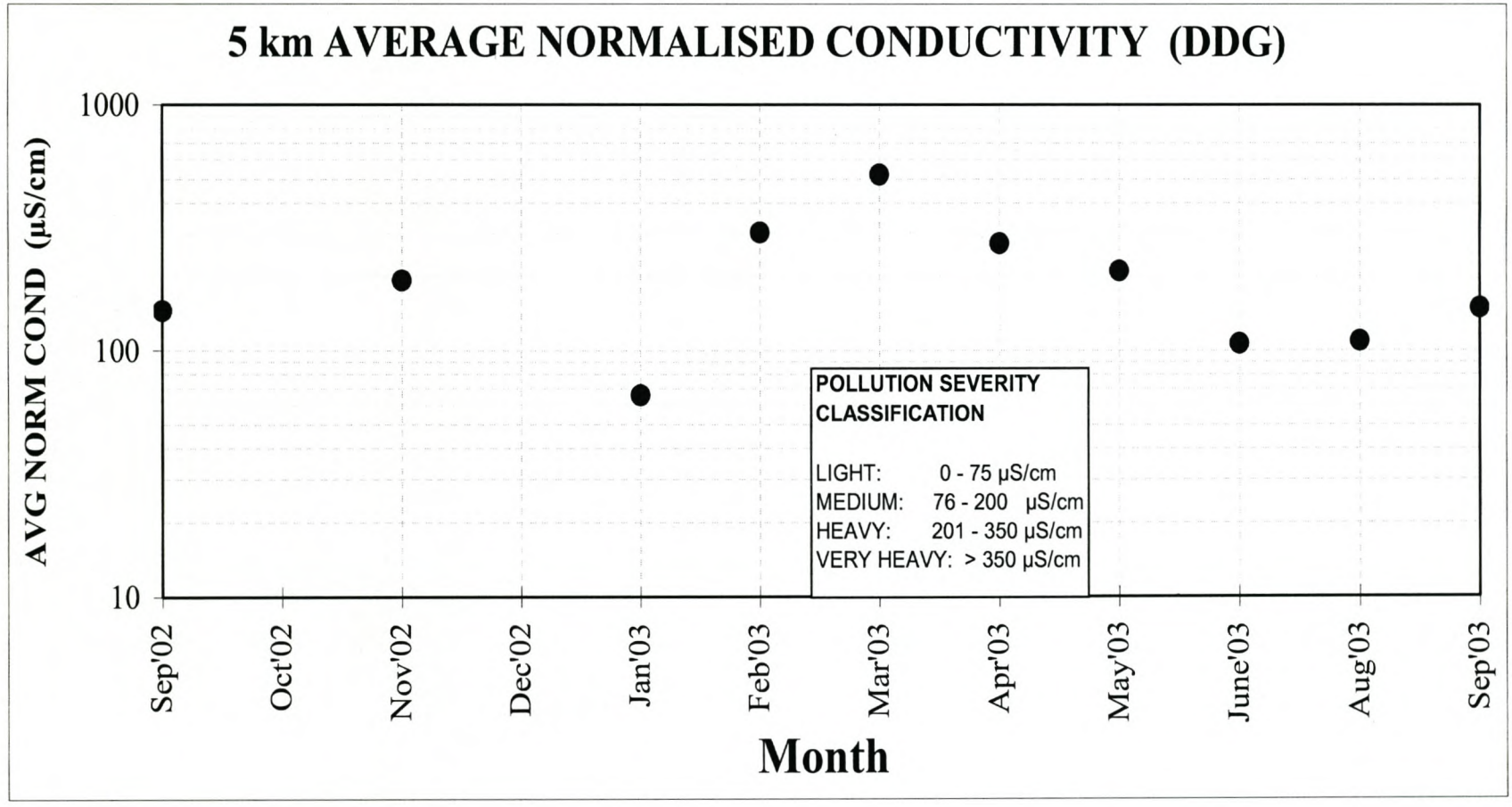


Fig. E.5 Plot of DDG measurements at the 5 km test site along the Koeberg – Muldersvlei 400 kV line

APPENDIX E: ESDD Measurements (Distance)

(1) 0.5 km from the sea: **Atlantic Substation**

ESDD Results: Disk 1

ATLANTIC SUB EQUIVALENT SALT DEPOSIT DENSITY (ESDD)

SEDIVER (U120 BS)

MONTH	V_COND distilled		V_COND uS/cm		TEMP		V_COND corr_20		VOLUME cm^3		AREA cm^2		ESDD mg/cm^2		ESDD1
	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	AVG
March '00	4.41	4.41	41.5	99.6	17.5	17.5	39.307	100.88	1000	1000	583.87	700.43	0.0342	0.0754	0.056663
April '00	2.54	2.54	58.4	99.5	18.5	18.5	57.825	100.37	1000	1000	583.87	700.43	0.051	0.075	0.0640491
May '00	1.63	1.63	27.8	48.8	15.5	15.5	29.098	52.448	1000	1000	583.87	700.43	0.0251	0.0384	0.0323711
June '00	1.54	1.54	17.17	48.2	15	15	17.592	52.518	1000	1000	583.87	700.43	0.015	0.0385	0.0277808
July '00	5.57	5.57	18.96	79.2	9.5	9.5	17.321	95.247	1000	1000	583.87	700.43	0.0147	0.071	0.045428
August '00	1.9	1.9	56.2	100.6	25	25	48.694	88.51	1000	1000	583.87	700.43	0.0427	0.0659	0.055324
September '00	4.95	4.95	24.4	70.7	16	16	21.366	72.226	1000	1000	583.87	700.43	0.0183	0.0534	0.0374378
October '00	4.45	4.45	39.2	83.9	20.5	20.5	34.358	78.554	1000	1000	583.87	700.43	0.0298	0.0582	0.0453139
November '00	4.85	4.85	56.4	105.9	24.5	24.5	46.713	91.568	1000	1000	583.87	700.43	0.0409	0.0682	0.0557902
December '00	6.35	6.35	148.8	178.5	26	26	125.14	151.24	1000	1000	583.87	700.43	0.1129	0.1143	0.1136746
January '01	2.06	2.06	36.8	105.7	25	25	31.153	92.94	1000	1000	583.87	700.43	0.0269	0.0693	0.0500204
February '01	1.86	1.86	54.7	99.4	27.5	27.5	45.048	83.155	1000	1000	583.87	700.43	0.0394	0.0618	0.0515929
March '01	3.64	3.64	45	107	24	24	37.876	94.654	1000	1000	583.87	700.43	0.033	0.0706	0.0534698
April '01	2.07	2.07	31.6	89.5	20.5	20.5	29.197	86.444	1000	1000	583.87	700.43	0.0252	0.0643	0.0465128
May '01	4.2	4.2	29.1	46.5	22	22	23.81	40.448	1000	1000	583.87	700.43	0.0204	0.0294	0.0253202
June '01	3.65	3.65	14.5	40.6	15.5	15.5	12.064	41.084	1000	1000	583.87	700.43	0.0101	0.0299	0.0209032
July '01	3.75	3.75	21.2	53.8	15	15	19.641	56.334	1000	1000	583.87	700.43	0.0168	0.0414	0.0301695
August '01	3.02	3.02	10.6	62.3	12	12	9.1947	71.908	1000	1000	583.87	700.43	0.0077	0.0532	0.0324836
September '01	4.78	4.78	40.3	79.7	19.5	19.5	35.928	75.781	1000	1000	583.87	700.43	0.0312	0.0561	0.044798
October '01	6.26	6.26	40.5	95.9	20	20	34.24	89.64	1000	1000	583.87	700.43	0.0297	0.0667	0.049892
November '01	7.87	7.87	36.6	75.1	25.5	25.5	25.499	59.669	1000	1000	583.87	700.43	0.0219	0.0439	0.0338959
December '01	4.11	4.11	38.3	92.9	24	24	31.31	81.312	1000	1000	583.87	700.43	0.0271	0.0603	0.0452263
January '02	1.36	1.36	28	83.4	24	24	24.396	75.13	1000	1000	583.87	700.43	0.0209	0.0556	0.0398612
February '02	3.33	3.33	48.6	98.6	28.5	28.5	37.85	79.655	1000	1000	583.87	700.43	0.0329	0.0591	0.0471933
March '02	4.82	4.82	33.4	68.6	24.7	24.7	25.79	57.554	1000	1000	583.87	700.43	0.0222	0.0423	0.0331399
April '02	2.25	2.25	129.2	205	19.4	19.4	128.7	205.55	1000	1000	583.87	700.43	0.1162	0.1569	0.1383614
May '02	1.32	1.32	98.2	145.3	17.9	17.9	101.71	151.15	1000	1000	583.87	700.43	0.0912	0.1143	0.1037716
June '02	6.56	6.56	174.4	216	15	15	188.91	235.73	1000	1000	583.87	700.43	0.1725	0.1806	0.1769309
July '02	12.9	12.9	159.4	182.6	15.3	15.3	163.69	189.61	1000	1000	583.87	700.43	0.1488	0.1443	0.1463777
August '02	5.82	5.82	13.93	54.5	15	15	9.1282	54.792	1000	1000	583.87	700.43	0.0076	0.0402	0.025376
September '02	2.3	2.3	21.6	54.3	18.3	18.3	20.072	54.081	1000	1000	583.87	700.43	0.0171	0.0396	0.0294136
October '02	2.78	2.78	80.3	158.3	17.5	17.5	82.154	164.82	1000	1000	583.87	700.43	0.0732	0.1249	0.1014013
November '02	2.19	2.19	41.6	114.6	19.4	19.4	39.955	113.96	1000	1000	583.87	700.43	0.0348	0.0854	0.0624274
December '02	3.62	3.62	40.6	85.3	22.8	22.8	34.748	76.75	1000	1000	583.87	700.43	0.0302	0.0569	0.0447211
January '03	2.65	2.65	34.9	126.4	20.6	20.6	31.815	122.08	1000	1000	583.87	700.43	0.0275	0.0917	0.0625374
February '03	5.39	5.39	98.2	138.2	24.7	24.7	83.75	119.85	1000	1000	583.87	700.43	0.0746	0.09	0.0830034
March '03	2.51	2.51	38.7	69.7	27.5	27.5	30.853	57.281	1000	1000	583.87	700.43	0.0267	0.0421	0.0350723
April '03	4.52	4.52	49.6	69.8	13.6	13.6	52.525	76.062	1000	1000	583.87	700.43	0.0462	0.0563	0.0517075
May '03	1.29	1.29	25.2	39.7	24.2	24.2	21.804	35.026	1000	1000	583.87	700.43	0.0187	0.0253	0.0223067
June '03	1.36	1.36	21.7	29.5	15.1	15.1	22.838	31.595	1000	1000	583.87	700.43	0.0196	0.0228	0.0213288
July '03	2.36	2.36	43.2	59.7	13.4	13.4	47.823	67.145	1000	1000	583.87	700.43	0.0419	0.0495	0.0460721
August '03	17.2	17.2	39.7	72.7	8.8	8.8	29.643	73.12	1000	1000	583.87	700.43	0.0256	0.0541	0.041142
September '03	31.4	31.4	60.2	118.1	15.1	15.1	32.337	97.346	1000	1000	583.87	700.43	0.028	0.0726	0.0523457
October '03	10.37	10.37	39.3	91.3	22.1	22.1	27.602	77.216	1000	1000	583.87	700.43	0.0238	0.0572	0.0420207
November '03	8.3	8.3	69.4	114	24.8	24.8	55.02	95.183	1000	1000	583.87	700.43	0.0484	0.071	0.0607181

APPENDIX E: ESDD Measurements (Distance)

ATLANTIC SUB EQUIVALENT SALT DEPOSIT DENSITY (ESDD)

DISK 2

MONTH	V_COND distilled		V_COND uS/cm		TEMP		V_COND corr_20		VOLUME cm^3		AREA cm^2		ESDD mg/cm^2		ESDD2
	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	AVG
May '00	1.63	1.63	18	53.7	15.5	15.5	18.202	57.896	1000	1000	583.87	700.43	0.0155	0.0425	0.0302398
August '00	1.9	1.9	30.6	91.5	25	25	25.737	80.349	1000	1000	583.87	700.43	0.0221	0.0596	0.0425737
November '00	4.85	4.85	38.4	121.1	24.5	24.5	30.402	105.34	1000	1000	583.87	700.43	0.0263	0.0788	0.0549173
February '01	1.86	1.86	45.7	126.1	27.5	27.5	37.375	105.92	1000	1000	583.87	700.43	0.0325	0.0792	0.0579907
May '01	4.2	4.2	13.6	48.3	22	22	8.9883	42.169	1000	1000	583.87	700.43	0.0075	0.0307	0.0201404
August '01	3.02	3.02	16.7	61.2	12	12	16.594	70.573	1000	1000	583.87	700.43	0.0141	0.0522	0.0348473
November '01	7.87	7.87	32.6	87.2	25.5	25.5	21.949	70.408	1000	1000	583.87	700.43	0.0188	0.052	0.0369167
February '02	3.33	3.33	33.4	103.4	28.5	28.5	25.142	83.669	1000	1000	583.87	700.43	0.0216	0.0621	0.0437181
May '02	1.32	1.32	50.3	127.1	17.9	17.9	51.42	132.05	1000	1000	583.87	700.43	0.0452	0.0994	0.0747576
August '02	5.82	5.82	14.2	42.7	15	15	9.4321	41.51	1000	1000	583.87	700.43	0.0079	0.0302	0.0200446
November '02	2.19	2.19	28.7	103.5	19.4	19.4	26.876	102.71	1000	1000	583.87	700.43	0.0231	0.0768	0.0523876
February '03	5.39	5.39	44	223	24.7	24.7	34.841	196.37	1000	1000	583.87	700.43	0.0302	0.1496	0.0953583
May '03	1.29	1.29	37.9	113.6	24.2	24.2	33.385	102.42	1000	1000	583.87	700.43	0.0289	0.0765	0.0548978
August '03	17.2	17.2	31.4	82.7	8.8	8.8	18.708	86.295	1000	1000	583.87	700.43	0.0159	0.0642	0.0422363
November '03	8.3	8.3	34.8	94.5	24.8	24.8	23.863	77.623	1000	1000	583.87	700.43	0.0205	0.0575	0.0406843

DISK 3

MONTH	V_COND distilled		V_COND uS/cm		TEMP		V_COND corr_20		VOLUME cm^3		AREA cm^2		ESDD mg/cm^2		ESDD3
	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	AVG
August '00	1.9	1.9	29.7	50.5	25	25	24.93	43.582	1000	1000	583.87	700.43	0.0214	0.0317	0.0270519
February '01	1.86	1.86	48	125.7	27.5	27.5	39.336	105.58	1000	1000	583.87	700.43	0.0343	0.079	0.0586467
August '01	3.02	3.02	46.9	46.7	12	12	53.227	52.985	1000	1000	583.87	700.43	0.0468	0.0388	0.0424435
February '02	3.33	3.33	26.7	98.3	28.5	28.5	19.54	79.405	1000	1000	583.87	700.43	0.0167	0.0589	0.0396938
August '02	5.82	5.82	25.9	46	15	15	22.601	45.224	1000	1000	583.87	700.43	0.0194	0.033	0.0267885
February '03	5.39	5.39	65.6	221	24.7	24.7	54.332	194.56	1000	1000	583.87	700.43	0.0478	0.1482	0.1025647
August '03	17.2	17.2	26.5	93.5	8.8	8.8	12.253	100.52	1000	1000	583.87	700.43	0.0103	0.0751	0.0456326

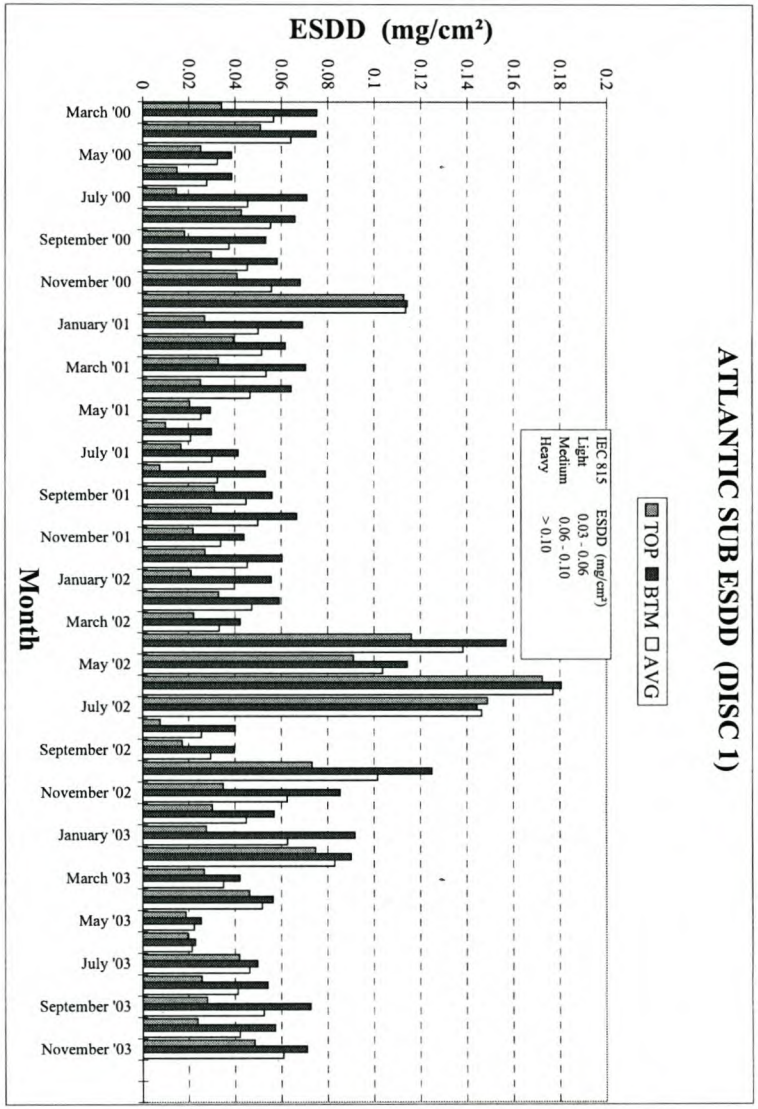
DISK 4

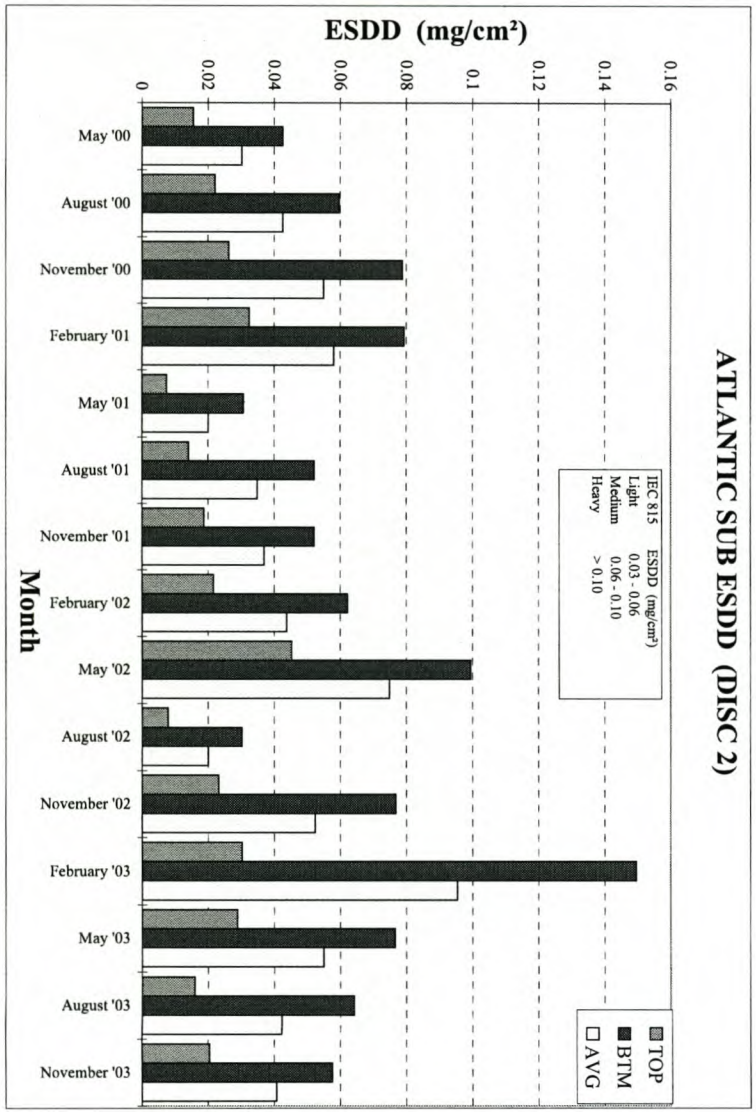
MONTH	V_COND distilled		V_COND uS/cm		TEMP		V_COND corr_20		VOLUME cm^3		AREA cm^2		ESDD mg/cm^2		ESDD4
	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	AVG
February '01	1.86	1.86	46.4	107.4	27.5	27.5	37.972	89.976	1000	1000	583.87	700.43	0.033	0.067	0.0515506
February '02	3.33	3.33	36.2	85.7	28.5	28.5	27.483	68.87	1000	1000	583.87	700.43	0.0237	0.0509	0.0385041
February '03	5.39	4.71	42.2	196.6	24.7	24.7	33.217	173.16	1000	1000	583.87	700.43	0.0288	0.1315	0.0847818

DISK 5

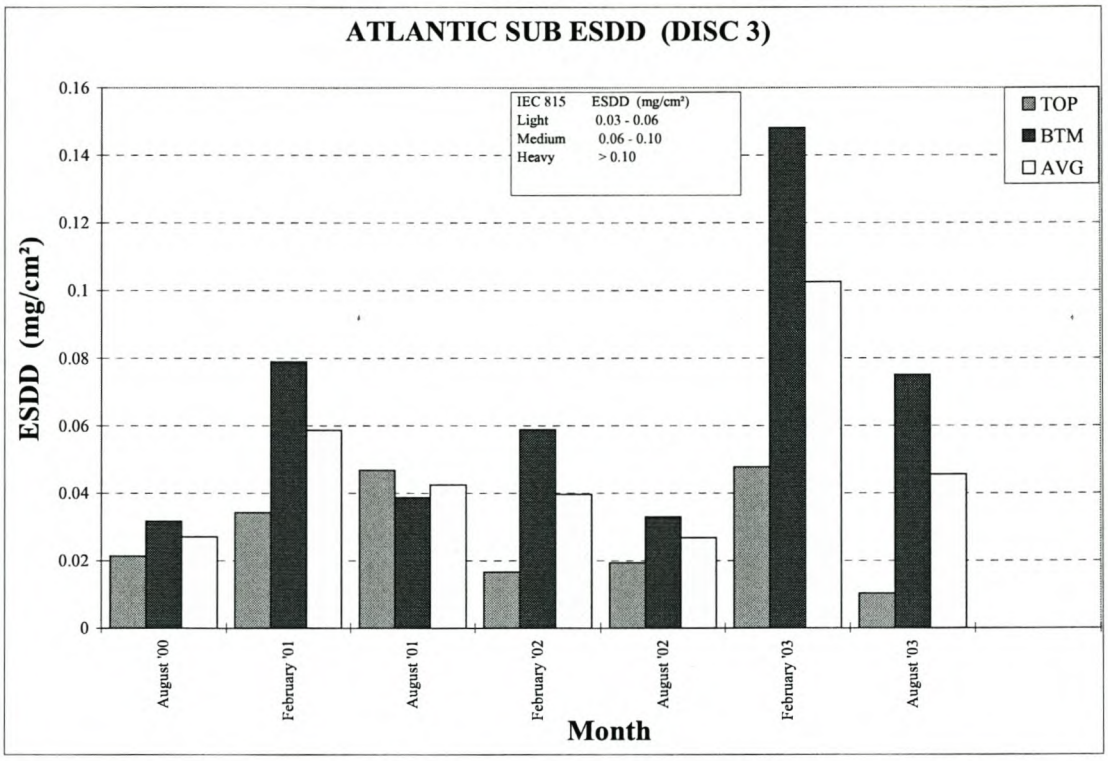
MONTH	V_COND distilled		V_COND uS/cm		TEMP		V_COND corr_20		VOLUME cm^3		AREA cm^2		ESDD mg/cm^2		ESDD5
	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	TOP	BTM	AVG
February '02	3.33	3.33	31.1	83.9	28.5	28.5	23.219	67.365	1000	1000	583.87	700.43	0.0199	0.0497	0.03616

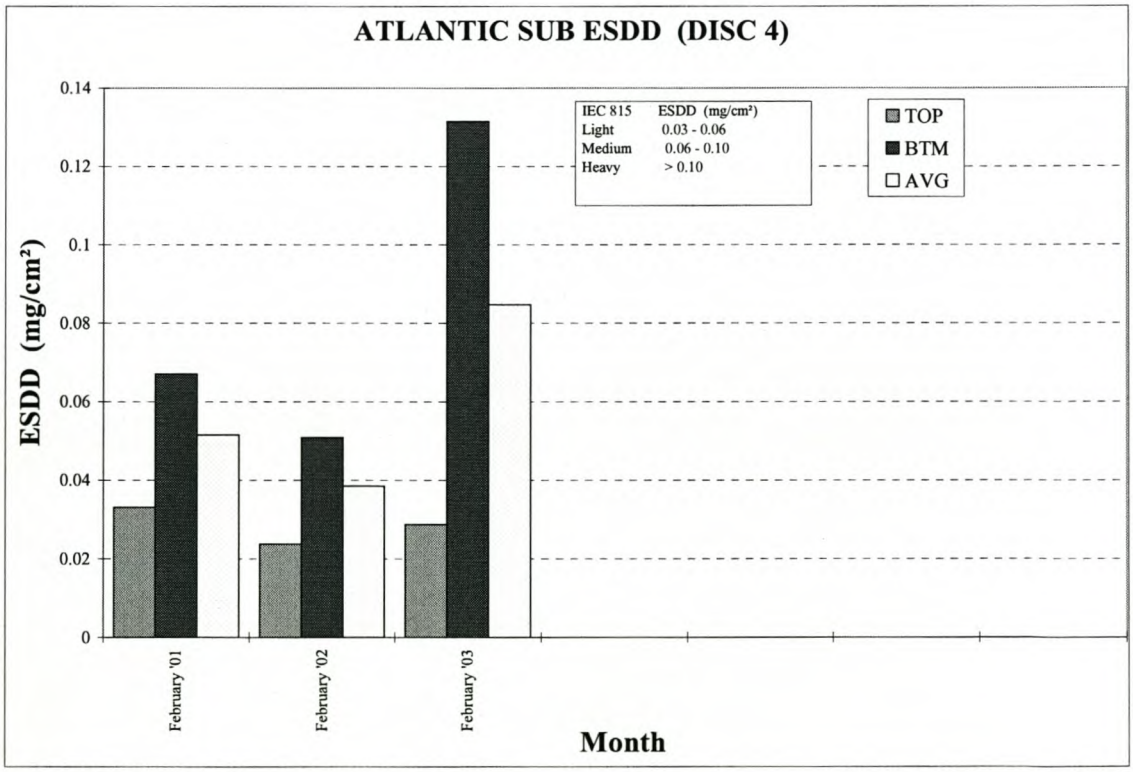
APPENDIX E: ESDD Measurements (Distance)



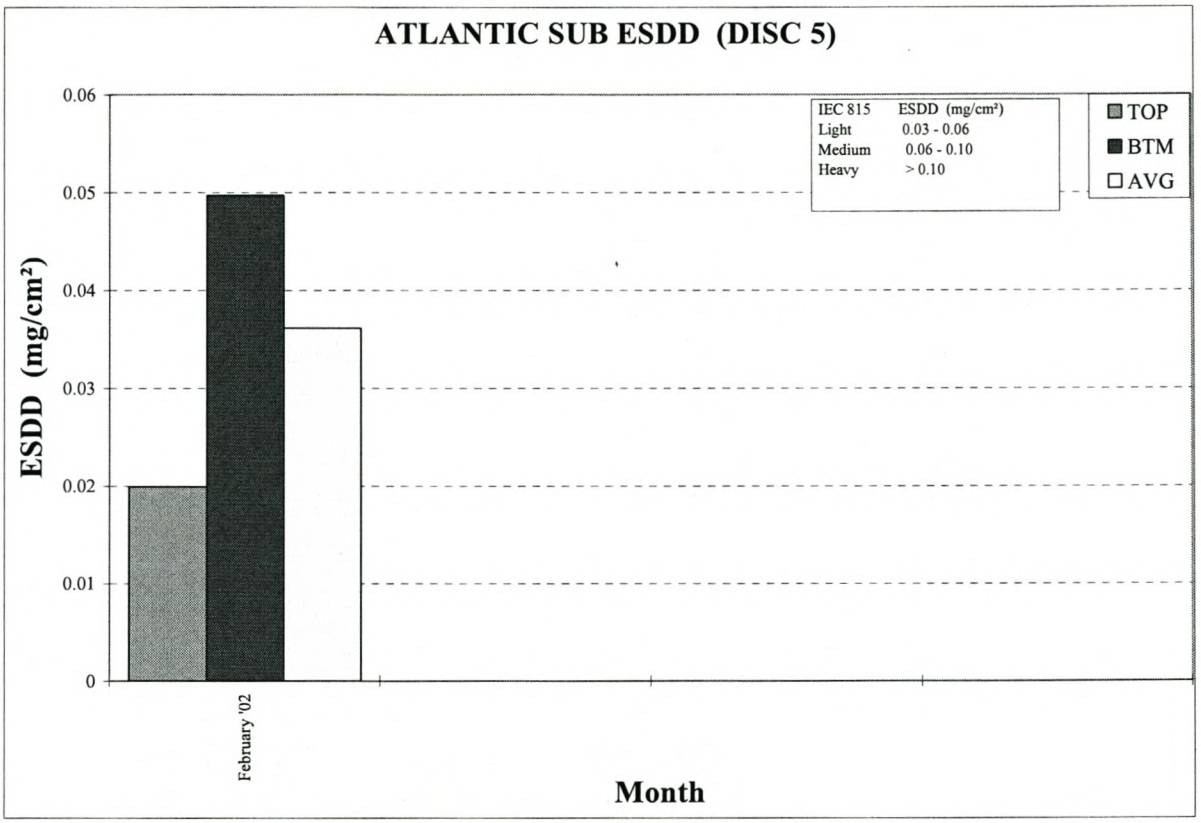


APPENDIX E: ESDD Measurements (Distance)





APPENDIX E: ESDD Measurements (Distance)



(1) **HEIGHT: 10 m** Date installed: 19 – 02 – 2002

DATE	RAIN	V_CNDd	VOLUME_CONDUCTIVITY (uS/cm)				SOLUTION VOLUME (cm^3)				DAYS	NORM_CONDUCTIVIY (uS/cm)				AVG_C
	(mm)	uS/cm	NORTH	EAST	SOUTH	WEST	NORTH	EAST	SOUTH	WEST		NORTH	EAST	SOUTH	WEST	uS/cm
Apr'02	810		498	1078	596	72.6	1000	500	500	500	52	574.62	621.92	343.85	41.88	395.57
Jun'02	850	2.41	491	707	794	37.8	500	500	500	500	61	240.29	346.52	389.31	17.40	248.38
Jul'02	600	3.9	454	575	834	578	500	500	500	500	47	287.30	364.53	529.85	366.45	387.03
Sep'02	1000	3	481	786.67	297	1432	500	500	500	1000	54	265.56	435.37	163.33	1587.78	613.01
Nov'02	650	15.5	996	268	572	1883	500	500	500	1000	55	534.82	137.73	303.55	2037.27	753.34
Jan'03		4.43	517	2380	1390	583	500	500	500	500	77	199.70	925.55	539.83	225.42	472.62
Feb'03	100	11.9	695	1252	917	1907	500	500	500	500	33	621.00	1127.36	822.82	1722.82	1073.50
Mar'03	700	15.4	483	736	349	864	500	500	500	1000	29	483.72	745.45	345.10	1755.72	832.50
Apr'03	510	10.1	137.8	325	105.8	533	500	500	500	500	34	112.68	277.85	84.44	461.38	234.09
May'03	1000	9.09	162.4	362	114.8	234	500	500	500	1000	35	131.41	302.49	90.61	385.56	227.52
Jun'03		42.3	65.5	224	50.6	267	500	500	500	500	28	24.86	194.68	8.89	240.75	117.29
Jul'03	1000	12.94	175.7	405	158.6	392	1000	1000	500	1000	34	287.22	691.87	128.52	668.93	444.14
Aug'03	1000	43.3	313	640	492	786	1000	1000	1000	500	42	385.29	852.43	641.00	530.50	602.30
Sep'03	720	40.1	228	558	122	457	500	1000	500	1000	25	225.48	1242.96	98.28	1000.56	641.82

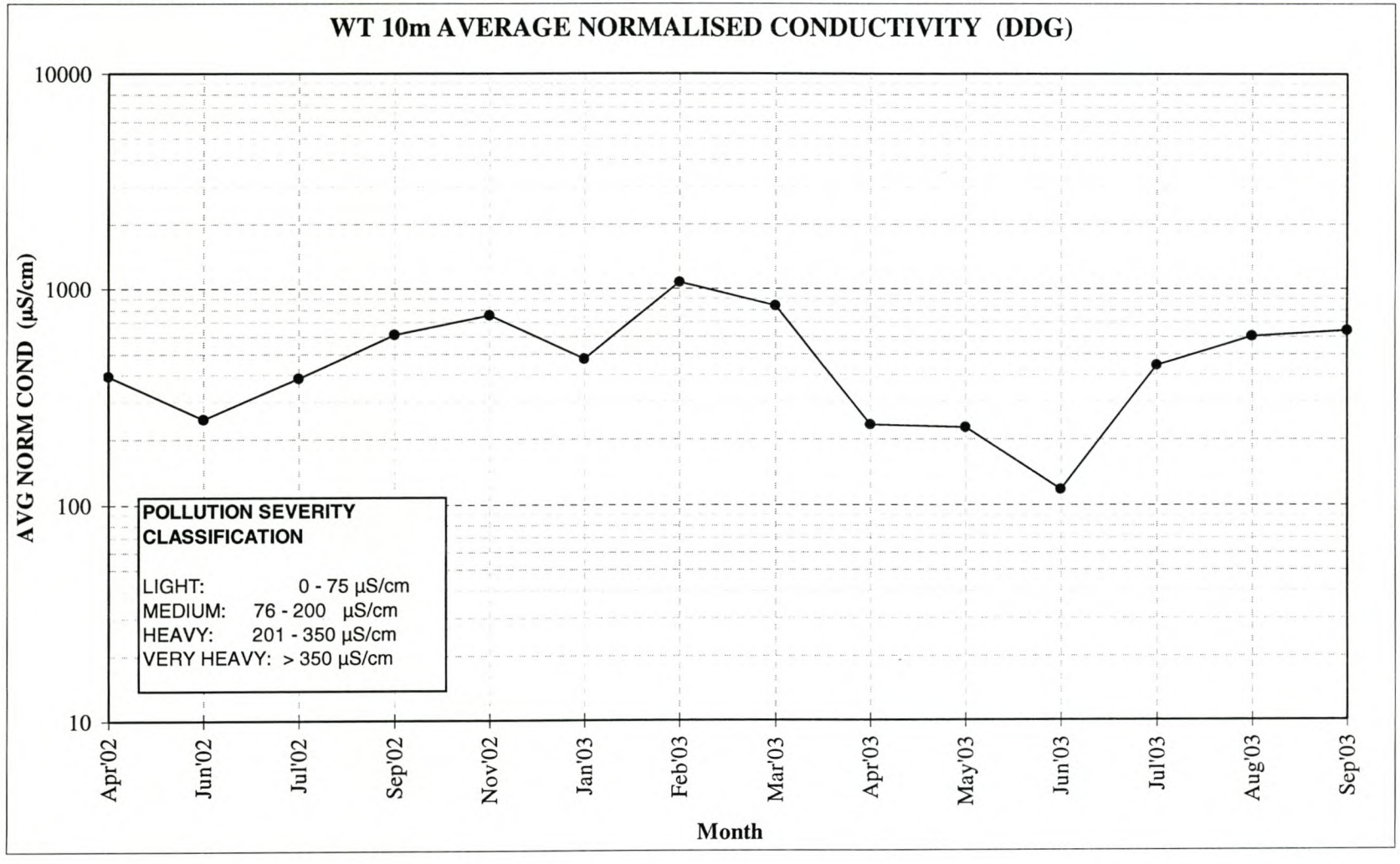


Fig. F.1 DDG measurements at 10 m test height on 120m high weather mast at the Koeberg-Weathers station

(2) **HEIGHT: 50 m** Date installed: 19 – 04 – 2002

DATE	RAIN	V_CNDd	VOLUME_CONDUCTIVITY (uS/cm)				SOLUTION VOLUME (cm^3)				DAYS	NORM_CONDUCTIVIY (uS/cm)				AVG_C
	(mm)	uS/cm	NORTH	EAST	SOUTH	WEST	NORTH	EAST	SOUTH	WEST		NORTH	EAST	SOUTH	WEST	uS/cm
Jun'02	710	2.41	424	84.5	406	503	1000	500	500	1000	54	468.43	45.61	224.22	556.21	323.62
Jul'02	640	3.9	306	686	36.1	362	500	500	500	500	47	192.83	435.38	20.55	228.57	219.34
Sep'02	1000	3	617	662	369	856	1000	500	500	1000	54	682.22	366.11	203.33	947.78	549.86
Nov'02	1000	15.5	1168	896	509	1046	1000	500	500	500	55	1257.27	480.27	269.18	562.09	642.20
Jan'03	50	25.4	1998	1201	1496	2320	500	500	500	500	77	768.55	458.03	572.96	894.00	673.38
Feb'03	90	11.9	1843	1249	1190	1446	500	500	500	500	33	1664.64	1124.64	1071.00	1303.73	1291.00
Mar'03	800	10.8	912	1307	1052	533	1000	500	500	500	29	1864.55	1340.90	1077.10	540.21	1205.69
Apr'03	820	6.3	261	157	722	417	1000	500	500	500	34	449.47	132.97	631.50	362.38	394.08
May'03	1000	17.65	186	123.3	303	224.5	1000	500	500	1000	35	288.60	90.56	244.59	354.60	244.59
Jun'03		10.44	295	89.5	231	200	500	500	500	500	28	304.89	84.71	236.31	203.10	207.25
Jul'03	1000	12.01	294	517		368	500	500		1000	34	248.81	445.58		628.22	440.87
Aug'03	1000	13.3	316	598	362	639	1000	500	1000	1000	42	432.43	417.64	498.14	893.86	560.52
Sep'03	680	17.6	322.5	194	409	568	1000	500	500	500	25	731.76	211.68	469.68	660.48	518.40

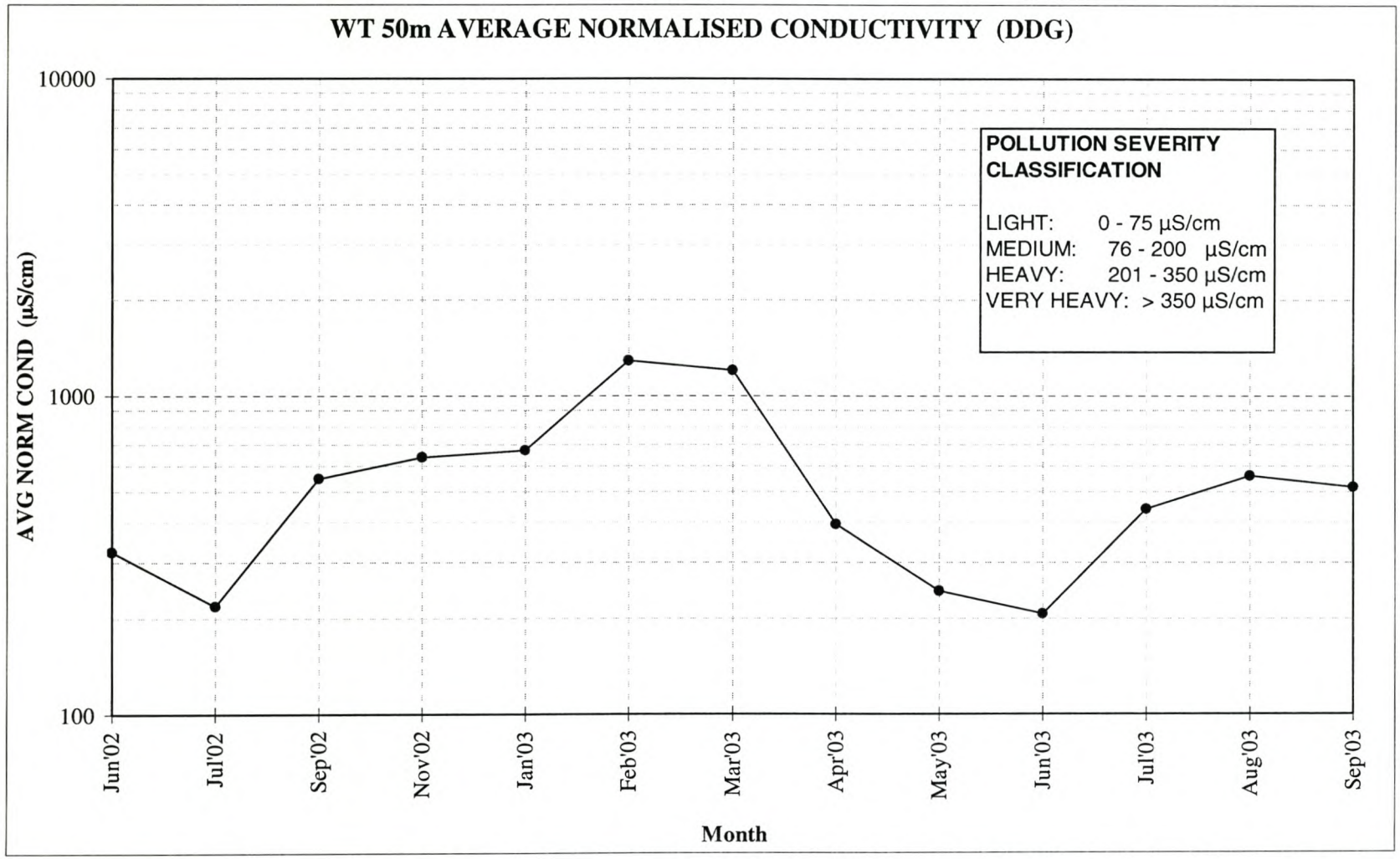


Fig. F.2. DDG measurements at 50 m test height on 120m high weather mast at the Koeberg-Weathers station

(3) **HEIGHT: 80m** Date installed: 15 – 11 – 2002

DATE	RAIN	V_CNDd	VOLUME_CONDUCTIVITY (uS/cm)				SOLUTION VOLUME (cm^3)				DAYS	NORM_CONDUCTIVIY (uS/cm)				AVG_C
	(mm)	uS/cm	NORTH	EAST	SOUTH	WEST	NORTH	EAST	SOUTH	WEST		NORTH	EAST	SOUTH	WEST	uS/cm
Jan'03		25.4	3430	1929.67	785	1574	500	500	500	500	77	1326.47	741.92	295.95	603.35	741.92
Feb'03		11.9	343	1514	514	1059	500	500	500	500	34	292.15	1325.38	443.03	923.91	746.12
Mar'03	250	13.1	181.3	203	554	417	500	500	500	500	28	180.21	203.46	579.54	432.75	348.99
Apr'03	290	2.45	156.5	186.3	188.6	229	500	500	500	500	34	135.93	162.22	164.25	199.90	165.57
May'03	800	11.6	89.4	75.5	128.2	85.5	1000	500	500	1000	35	133.37	54.77	99.94	126.69	103.69
Jun'03		10.73	56.5	58.5	78.6	74.5	500	500	500	500	28	49.04	51.18	72.72	68.33	60.32
Jul'03	1000	5.75	193	181	213	186	1000	500	500	1000	34	330.44	154.63	182.87	318.09	246.51
Aug'03	1000	14.9	222	191.9	285	731	1000	500	1000	500	42	295.86	126.43	385.86	511.50	329.91
Sep'03	480	32.9	199	137	170.8	212	500	500	500	500	25	199.32	124.92	165.48	214.92	176.16

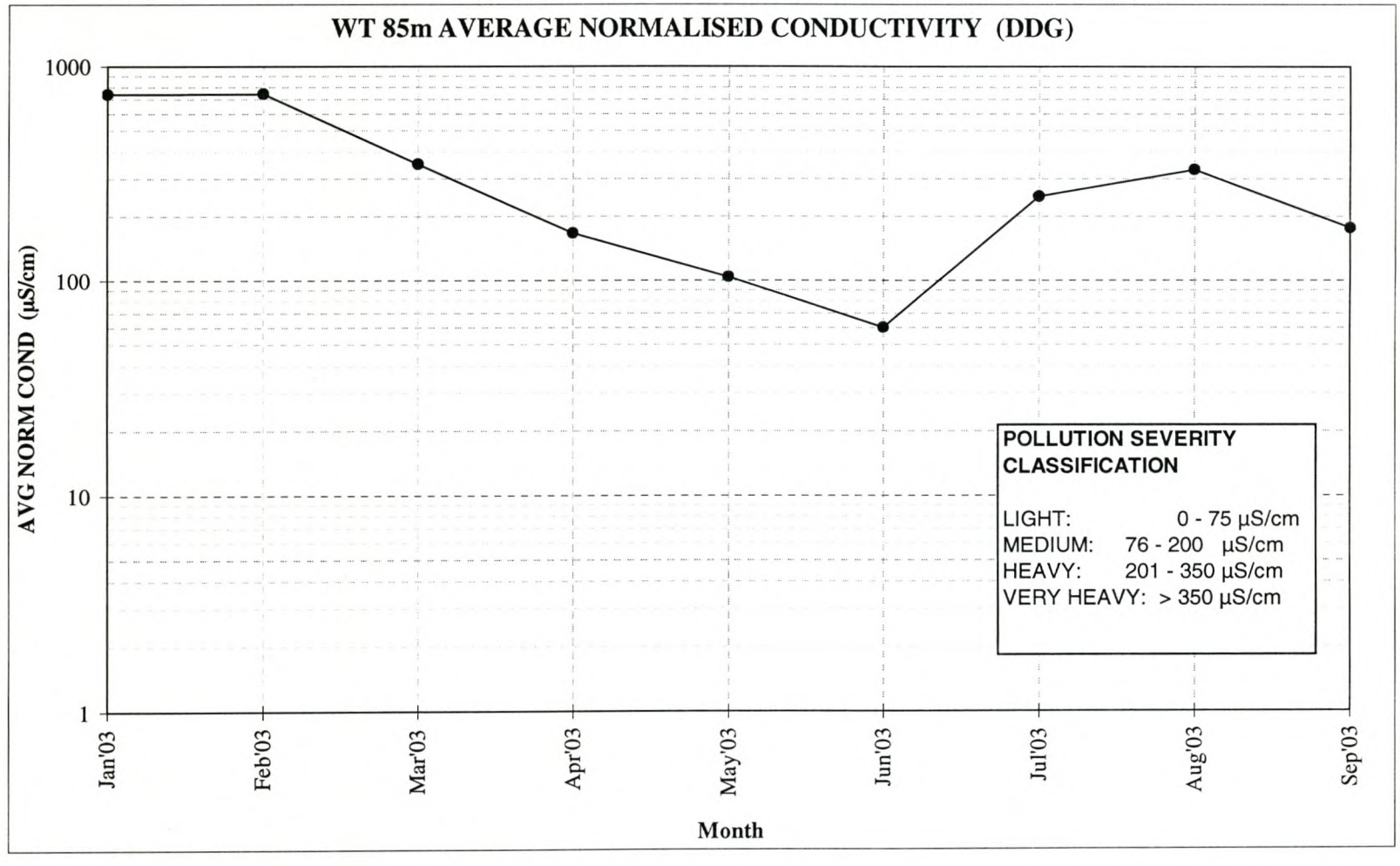


Fig. F.3 DDG measurements at 85 m test height on 120m high weather mast at the Koeberg-Weathers station

(4) **Height: 120 m** Date installed: 31 – 01 – 2003

DATE	RAIN	V_CNDd	VOLUME_CONDUCTIVITY (uS/cm)				SOLUTION VOLUME (cm^3)				DAYS	NORM_CONDUCTIVIY (uS/cm)				AVG_C
	(mm)	uS/cm	NORTH	EAST	SOUTH	WEST	NORTH	EAST	SOUTH	WEST		NORTH	EAST	SOUTH	WEST	uS/cm
Feb'03	60	11.9	405	1635	536	1663	500	500	500	500	34	346.85	1432.15	462.44	1456.85	924.57
Mar'03	410	5.3		644	936	1116	500	500	500	500	28		684.32	997.18	1190.04	957.18
Apr'03	480	17.01	306	202	458	367	500	500	500	500	34	254.99	163.23	389.11	308.81	279.04
May'03	1000	22	176.1	38.1	221	186.4	1000	500	1000	1000	35	264.17	13.80	341.14	281.83	225.24
Jun'03		3.45	105.5	92.4	294	245	500	500	500	500	28	109.34	95.30	311.30	258.80	193.69
Jul'03	1000	5.72	192	197	199	176	1000	500	1000	1000	34	328.73	168.78	341.08	300.49	284.77
Aug'03	1000	9.18	165.2	344	257	310	1000	500	1000	1000	42	222.89	239.16	354.03	429.74	311.45
Sep'03	500	28.7	412	152.8	536	408	500	500	500	1000	25	459.96	148.92	608.76	910.32	531.99

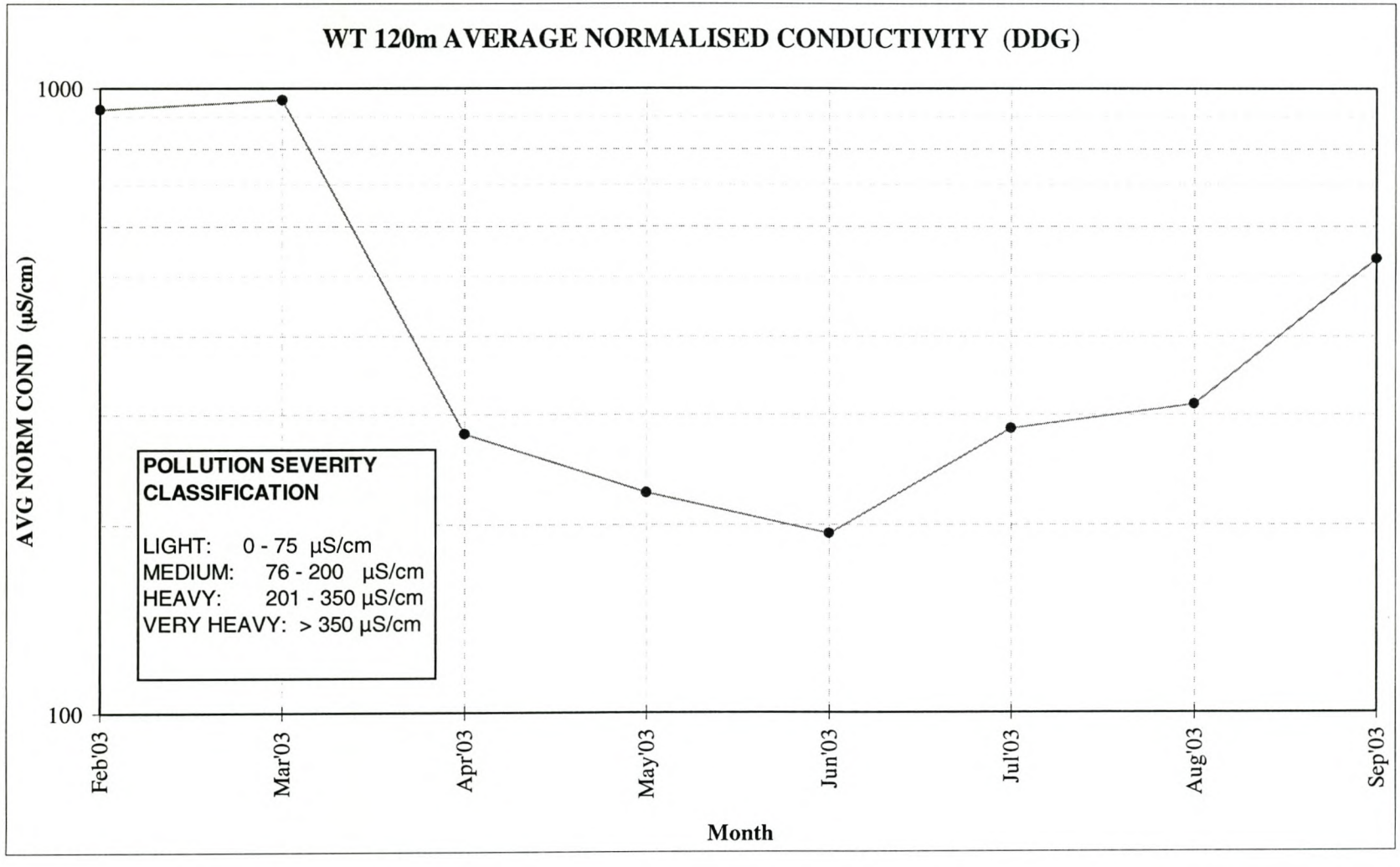


Fig. F.4 DDG measurements at 120 m test height on 120m high weather mast at the Koeberg-Weathers station

1. Distance from Coast

CLIMAT (wire-on-bolt) Test results: Average 98- day exposure duration(March to August 2003)

Location: Koeberg-Muldersvlei 400kV servitude area, up to 30 km inland

Description			Mass Loss			ASTM G116		ISO 9226 (9223)	
Site	time (days)	specimen	Om (g)	Fm (g)	mL (mg)	mL90 (g)	GE (%)	Rate (um/a)	CLASS
KIPTS	90	Reference	1.3271	1.3351	-8.0				
		Al-Fe	1.3295						
40 m		Al-Cu	1.3362						
800m	98	Reference	1.3175	1.3775	-60.0	0.0455			
		Al-Fe	1.3192	1.2349	84.3	0.0639	0.37	51.766	C4
Mast 3 m		Al-Cu	1.3174						
1 km	97	Reference	1.3578	1.3588	-1.0	0.0007			
		Al-Fe	1.3352	1.222	113.2	0.0848	10.588	69.387	C4
		Al-Cu	1.3324	1.0417	290.7	0.2182	27.394	17.8563	C5
2 km	97	Reference	1.3426	1.3477	-5.1	0.0038			
		Al-Fe	1.3316	1.2971	34.5	0.0259	5.40	21.204	C2
		Al-Cu	1.3235	1.2939	29.6	0.0224	4.53	1.8304	C4
3 km	97	Reference	1.3241	1.3297	-5.6	0.0042			
		Al-Fe	1.3262	1.2758	50.4	0.0380	7.41	31.103	C3
		Al-Cu	1.3338	1.2974	36.4	0.0273	5.06	2.2335	C4
4 km	97	Reference	1.3195	1.324	-4.5	0.0034			
		Al-Fe	1.3284	1.2895	38.9	0.0293	7.04	23.966	C2
		Al-Cu	1.3187	1.2962	22.5	0.0171	3.71	1.3964	C3
5 km	98	Reference	1.2936	1.2915	2.1	0.0016			
		Al-Fe	1.3103	1.2697	40.6	0.0310	16.61	25.100	C3
		Al-Cu	1.3123	1.271	41.3	0.0315	16.89	2.5494	C4

6 km	91	Reference	1.3249	1.3274	-2.5	0.0019			
		Al-Fe	1.3162	1.2474	68.8	0.0523	26.41	45.601	C3
		Al-Cu	1.321	1.2921	28.9	0.0219	10.48	1.9086	C4
9 km	91	Reference	1.3114	1.3231	-11.7	0.0089			
		Al-Fe	1.3253	1.3168	8.5	0.0064	-0.28	5.595	C2
		Al-Cu	1.3155	1.3081	7.4	0.0056	-0.37	0.4907	C2
10 km	94	Reference	1.3268	1.3315	-4.7	0.0035			
		Al-Fe	1.3269	1.2875	39.4	0.0297	7.07	25.077	C3
		Al-Cu	1.3158	1.2728	43.0	0.0327	7.88	2.7600	C4
15 km	91	Reference	1.3127	1.3183	-5.6	-5.1959			
		Al-Fe	1.321	1.2862	34.8	32.2887	-7.14	22.982	C2
		Al-Cu	1.3114	1.2895	21.9	20.3196	-4.86	1.4.69	C4
20 km	92	Reference	1.3456	1.3522	-6.6	-6.1237			
		Al-Fe	1.3248	1.2997	25.1	23.2887	-4.70	16.349	C2
		Al-Cu	1.3189	1.2898	29.1	27.0000	-5.29	1.9039	C4
30 km	90	Reference	1.3318	1.3372	-5.4	-5.0103			
		Al-Fe	1.3267	1.3174	9.3	8.6289	-2.72	6.183	C2
		Al-Cu	1.3367	1.3272	9.5	8.8144	-2.76	0.6269	C3

2. Distance from Coast: Metal Coupons Test results: Average 220-day exposure duration (March to November 2003)

Location: Koeberg-Muldersvlei 400kV servitude area, up to 30 km inland

Description			Mass Loss			Surface area				Corrosion Rate		ISO 9223 & 9226	
Site	time (days)	specimen	Om (g)	Fm (g)	mL (g)	L (mm)	W (mm)	h (mm)	Area m^2	Rate (um/a)	CLASS	Rate ($g/m^2.a$)	CLASS ($g/m^2.a$)
KIPTS 40 m	229	mild Fe	118.7	121.6556	-3.1155	101	51	3	11.214	56.3378	C4	442.8152	C4
		galv Fe	114	114.6026	-0.4427	151	101	1	31.006	5.49	C5	22.7581	C2
800 m Mast 3 m	227	mild Fe	123	123.8800	-1.0399	99	49	3	10.59	20.0879	C2	20.0879	C2
		galv Fe	68.9	68.9508	-0.2107	149	99	1	29.998	1.5816	C3	11.2930	C2
1 km	224	mild Fe	120.9	121.6556	-0.9155	99	49	3	10.59	17.9216	C2	140.8640	C2
		galv Fe	68.7	68.5678	-0.0277	150	100	1	30.5	0.2072	C2	1.4791	C1
2 km	224	mild Fe	121.9	122.5364	-0.7963	99	49	3	10.59	15.5882	C2	122.5229	C2
		galv Fe	68.1	68.0748	-0.1347	150	100	1	30.5	1.0078	C3	7.1956	C1
3 km	224	mild Fe	125	125.3743	-0.2144	99	49	3	10.59	4.1974	C2	32.9917	C2
		galv Fe	67.6	67.5511	-0.1110	150	100	1	30.5	0.8304	C3	5.9294	C1
4 km	224	mild Fe	119.6	120.0825	-0.6424	99	49	3	10.59	12.5754	C2	12.5754	C2
		galv Fe	68.3	68.2720	-0.1319	150	100	1	30.5	0.9868	C3	7.0460	C1
5 km	224	mild Fe	121.9	122.2782	-0.5381	100	49	3	10.694	10.4312	C2	81.9890	C2
		galv Fe	68.3	68.3222	-0.1821	149	100	1	30.298	1.3715	C3	9.7928	C1
6 km	204	mild Fe	116.5	116.5089	-0.1688	101	50	3	11.006	3.4910	C2	27.4389	C2
		galv Fe	114	113.9719	0.1880	150	101	1	30.802	1.5294	C3	10.9196	C2
9 km	190	mild Fe	121.9	121.5582	0.1819	101	51	3	11.214	3.9648	C2	31.1636	C2
		galv Fe	114.4	114.3095	-0.0694	151	101	1	31.006	0.6021	C3	4.2989	C1
10 km	220	mild Fe	124	124.3736	-0.2137	99	49.5	3	10.692	4.2191	C2	33.1624	C2
		galv Fe	67.8	67.7137	-0.0736	151	101	1	31.006	0.5515	C2	3.9374	C1
15 km	204	mild Fe	116.2	115.9600	0.0801	101	49	3	10.798	1.6889	C2	13.2750	C2
		galv Fe	117.7	117.6403	-0.1002	151	101	1	31.006	0.8097	C3	5.7812	C1
20 km	218	mild Fe	122.7	122.9294	-0.3893	100	49	3	10.694	7.7543	C2	60.9486	C2
		galv Fe	68.4	68.2351	0.0050	150	99	1	30.198	0.0389	C1	0.2781	C1
30 km	183	mild Fe	124.3	124.5979	-0.4578	99	49	3	10.59	10.9694	C2	72.3772	C2
		galv Fe	114	113.9525	0.2074	150	100	1	30.5	1.5945	C3	11.3845	C2

3. Height above ground

CLIMAT (wire-on-bolt) Test results: Average 98-day exposure duration (5 March to 11 June 2003)

Location: Koeberg Weather Station, 120 m high mast

Description			Mass Loss			ASTM G116		ISO 9226 (9223)	
Height	time (days)	specimen	Om (g)	Fm (g)	mL (mg)	mL90 (g)	GE (%)	Rate (um/a)	CLASS
120m	98	Reference	1.3248	1.3314	-6.6				
		Al-Fe	1.3216						
		Al-Cu	1.3246						
85m	98	Reference	1.3235	1.3292	-5.7	0.0043			
		Al-Fe	1.3279	1.2725	55.4	0.0417	7.98	33.796	C3
		Al-Cu	1.3282						
50m	98	Reference	1.3035	1.3155	-12.0				
		Al-Fe	1.327						
		Al-Cu	1.3235						
10m	98	Reference	1.3184	1.3254	-7.0				
		Al-Fe	1.3229						
		Al-Cu	1.3338						
3m	98	Reference	1.3175	1.3775	-60.0	0.0455			
		Al-Fe	1.3192	1.2349	84.3	0.0639	0.37	51.766	C4
		Al-Cu	1.3174						

4. Height above ground

Metal Coupons Test results: Average 227-day exposure duration (5 March to 18 October 2003)

Location: Koeberg Weather Station, 120m high weather mast

Description			Mass Loss			Surface area				Corrosion Rate		ISO 9223 & 9226	
Height	time (days)	specimen	Om (g)	Fm (g)	mL (g)	L (mm)	W (mm)	h (mm)	Area m^2	Rate (um/a)	CLASS	Rate ($g/m^2.a$)	CLASS ($g/m^2.a$)
120m	227	mild Fe	123.7	124.3038	-0.7637	100	50	3	10.9	14.3328	C2	112.6561	C2
		galv Fe	68.3	68.3047	0.1552	150	100	1	30.5	1.1458	C3	8.1812	C1
		Al	79.7	79.8864	-0.0265	100	50	6	11.8	1.3382	-	3.6131	C4
85m	227	mild Fe	124.2	124.8343	-0.7942	100	49	3	10.694	15.1924	C2	119.4121	C2
		galv Fe	68.8	68.8409	-0.2008	149	100	1	30.298	1.4924	C3	10.6558	C2
50m	227	mild Fe	121.6	122.0853	-0.6452	99	49	3	10.59	12.4633	C2	97.9615	C2
		galv Fe	67.6	67.8005	-0.3604	149	99	1	29.998	2.7055	C4	19.3171	C2
10m	227	mild Fe	122	122.617	-0.4571	99	49	3	10.59	8.8303	C2	69.4059	C2
		galv Fe	68.5	68.6629	-0.3228	150	99	1	30.198	2.4072	C4	17.1871	C2
		Al	82.1022	82.2915	-0.0294	100	50	6	11.8	1.4845	-	4.0082	C4
3m	227	mild Fe	123	123.88	-1.0399	99	49	3	10.59	20.0879	C2	20.0879	C2
		galv Fe	68.9	68.9508	-0.2107	149	99	1	29.998	1.5816	C3	11.2930	C2

A. Procedure: Atmospheric Corrosion Testing

This procedure is based on the ASTM G1 – 90 standard [23].

1. SCOPE

This practice covers suggested procedures for preparing bare, solid metal specimens for tests, for removing corrosion products after the test has been completed, and for evaluating the corrosion damage that has occurred. Emphasis is placed on procedures related to the evaluation of corrosion by mass loss measurements.

2. SIGNIFICANCE AND USE

Preparing and Cleaning of Specimens before testing

The procedures given are designed to remove corrosion products without significant removal of base material. This allows an accurate determination of mass loss of the metal or alloy that occurred during exposure to the corrosive environment.

3. DESCRIPTION

The corrosion testing procedure can be divided into four steps:

1. Reagents and materials
2. Labelling/marking of specimens
3. Preparing and Cleaning of Specimens before testing,
4. Method of corrosion testing,
5. Removing corrosion products after testing, and
6. Evaluating of corrosion

3.1 Reagents and Materials

Purity of Reagents – Reagent grade chemicals shall be used in all tests.

Purity of Water – Unless otherwise indicated, references to water shall be understood to mean reagent.

3.2 Labelling/Marking of specimens

It is desirable to mark specimens used in corrosion tests with a unique designation during preparation. Several techniques may be used depending on the specimen and test.

1. *Stencil or Stamp* – most metallic specimens may be marked by stencilling, that is, imprinting the designation code into the metal surface using hardened steel stencil stamps hit with a hammer. The resulting imprint will be visible even after substantial corrosion has occurred. However, this procedure introduces localized strained regions and the possibility of superficial iron contamination in the marked area.

2. *Electric engraving* by means of a vibratory marking tool may be used when the extent of corrosion damage is known to be small. However, this approach to marking is much more susceptible to having the marks lost as a result of corrosion damage during testing.

3. *Edge notching* is especially applicable when extensive corrosion and accumulation of corrosion products is anticipated. Long term atmospheric tests and sea water immersion tests on steel are examples where this approach is applicable. It is necessary to develop a code system when using edge notches.

4. *Drilled holes* may be used to identify specimens when extensive metal loss, accumulation of corrosion products, or heavy scaling is anticipated. Drilled holes may be simpler and less costly than edge notching. A code system must be developed when using drilled holes. Punched holes should not be used as they introduce residual strain.

5. When it is undesirable to deform the surface of specimens after preparation procedures, for example, when testing coated surfaces, *tags* may be used for specimen identification. A metal or plastic wire can be used to attach the tag to the specimen and the specimen identification can be stamped on the tag. It is important to ensure that neither the tag nor the wire will corrode or degrade in the test environment. It is also important to be sure there are no galvanic interaction between the tag, wire, and specimen.

NOTE: For this project, the following methods were used:

- *CLIMAT (wire-on-bolt) specimens: specimens were marked on the Perspex plate, and upon removal it was placed in a 'marked' envelope or rolled in 'marked' paper.*
- *Metal coupons were stencilled and rolled in 'marked paper*

3.3 Preparing and cleaning specimens before testing

3.3.1 For more searching tests on either the metal or the environment, standard surface finishes may be preferred. A suitable procedure might be:

- Degrease in an organic solvent or hot alkaline cleaner.

  Note 1 – Hot alkalies and chlorinated solvents may attack some metals.

  Note 2 – Ultrasonic cleaning ma y be beneficial in both pre-test and post-test cleaning procedures.

- Pickle in an appropriate solution if oxides or tarnish are present. In some cases the chemical cleaners will suffice.

  Note 3 – Pickling may cause localized corrosion on metals.

- Rinse thoroughly, hot air dry, and store in desiccator.

3.3.2 The clean, dry specimen should be measured and weighed. Dimensions should be to the third significant figure and mass determined to the fifth significant figure are suggested. When more significant figures are available on the measuring instruments, they should be recorded.

3.4 Method of Corrosion Testing

The method of test (CLIMAT or coupons or other) would then determine the criteria for exposure. For CLIMAT, it would be a 90-day exposure; for metal coupons, the exposure times can range from moths to years.

3.5 Method of cleaning after testing

Corrosion product removal procedures can be divided into three categories:

- mechanical,
- chemical, and
- electrolytic.

3.5.1 Mechanical cleaning

Mechanical procedures can include scraping, scrubbing, brushing, ultrasonic cleaning, mechanical shocking, and pact blasting (for example, grit blasting, water-jet blasting and so forth). These methods are often utilized to remove heavily encrusted corrosion products. Scrubbing with a non-metallic bristle brush and a mild abrasive-distilled water slurry can also be used to remove corrosion products. Two approaches are discussed below:

3.5.1.1 Lightly Corroded Specimens

An ideal procedure should remove only corrosion products and not result in removal of any base metal. To determine the mass loss of the base metal when removing corrosion products, replicate uncorroded control

specimens should be cleaned by the same procedure being used on the test specimen. By weighing the control specimen before and after cleaning, the extent of metal loss resulting from cleaning can be utilised to correct the corrosion mass loss.

Note: It is desirable to scrape samples of corrosion products before using any chemical techniques to remove them. These scrapings can then be subjected to various forms of analyses, including perhaps X-ray diffraction to determine crystal forms as well as chemical analyses to look for specific corrodants, such as chlorides. All of the chemical techniques that are discussed in Section 7 tend to destroy the corrosion products and thereby lose the information contained in these corrosion products. Care may be required so that uncorroded metal is not removed with the corrosion products.

- To decide upfront:
  Corrosion products will be analysed? if YES : then no chemical techniques for cleaning should be used
  If NO : chemical techniques for cleaning can be used

3.5.1.2 Heavily Corroded Specimens – Repetitive cleaning cycles

The procedure given in 3.5.1 may not be reliable when heavily corroded specimens are to be cleaned. The application of replicate cleaning procedures to specimens with corroded surfaces will often, even in the absence of corrosion products, result in continuing mass losses. This is because a corroded surface, particularly of a multiphase alloy, is often more susceptible than a freshly machined or polished surface to corrosion by the cleaning procedure. In such cases, the following method of determining the mass loss due to the cleaning procedure is preferred.

1) The cleaning procedure should be repeated on specimens several times. The mass loss should be determined after each cleaning by weighing the specimen.
2) The mass loss should be graphed as a function of the number of equal cleaning cycles as shown in Fig. 1. Two lines will be obtained: AB and BC. The latter will correspond to corrosion of the metal after removal of corrosion products. The mass loss due to corrosion will correspond approximately to point B.
3) To minimize uncertainty associated with corrosion of the metal by the cleaning method, a method should be chosen to provide the lowest slope (near to horizontal) of line BC.

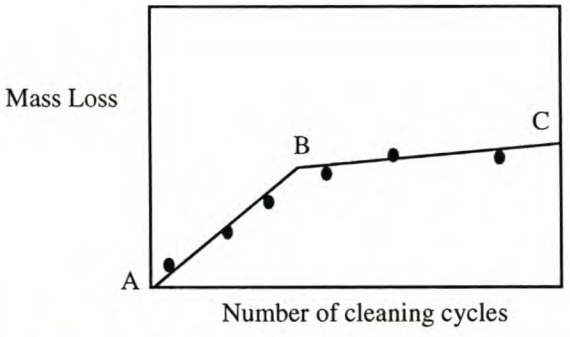


Fig. 1 Mass Loss of Corroded Specimens Resulting From Repetitive Cleaning Cycles

Repeated treatment may be required for complete removal of corrosion products. Removal can often be confirmed by examination with a low power microscope (for example, 7X to 30X). This is particularly useful with pitted surfaces when corrosion products may accumulate in pits. This repeated treatment may also be necessary because of the requirements of (1). Following the final treatment, the specimens should be thoroughly rinsed and immediately dried.

All cleaning solutions shall be prepared with water and reagent grade chemicals.

3.5.2 Chemical cleaning

Chemical Procedures involve immersion of the corrosion test specimen in a specific solution that is designed to remove the corrosion products with minimal dissolution of any base metal. Several procedures listed in Table A1.1 specify the chemical procedures to be used for the specific metal and type of corrosion product scale.

Note – **Caution:** These methods may be hazardous to personnel.

- Chemical cleaning is often preceded by light brushing (non metallic bristle) or ultrasonic cleaning of the test specimen to remove loose, bulky corrosion products.
- Intermittent removal of specimens from the cleaning solution for light brushing or ultrasonic cleaning can often facilitate the removal of tightly adherent corrosion products.
- Chemical cleaning is often followed by light brushing or ultrasonic cleaning in reagent water to remove loose products.

Table A1.1 Chemical Cleaning Procedures for Removal of Corrosion Products

Designation	Material	Solution	Time	Temperature	Remarks
C.1.1	Aluminium and Aluminium Alloys	50 mL phosphoric acid (H_3PO_4, sp gr 1.69) 20 g chromium trioxide (CrO_3) Reagent water to make 1000 mL	5 to 10 min	90°C Boiling	If corrosion product films remain, rinse, then follow with nitric acid procedure (C.1.2).
C.1.2		Nitric acid (HNO_3, sp gr 1.42)			Remove extraneous deposits and bulky corrosion products to avoid reactions that may result in excessive removal of base metal.
C.2.1	Copper and Copper Alloys	500 mL hydrochloric acid (HCL, sp gr 1.19) Reagent water to make 1000 mL	1 to 3 min	20 to 25°C	Deaeration of solution with purified nitrogen will minimizes base metal removal
C.2.2		4.9g sodium cyanide (NaCN) Reagent water to make 1000 mL	1 to 3 min	20 to 25°C	Removes copper sulphide corrosion products that may not be removed by hydrochloric acid treatment (C.2.1)
C.3.1	Iron and Steel	1000 mL hydrochloric acid (HCL, sp gr 1.19) 20g antmony trioxide (Sb_2O_3) 50g stannous chloride ($SnCl_2$) Reagent water to make 1000 mL	1 to 25 min	20 to 25°C	Solution should be vigorously stirred or specimen should be brushed.

3.5.3 Electrolytic cleaning

- Electrolytic cleaning should be preceded by brushing or ultrasonic cleaning of the test specimen to remove loose, bulky corrosion products.

3.6 Assessment of corrosion damage

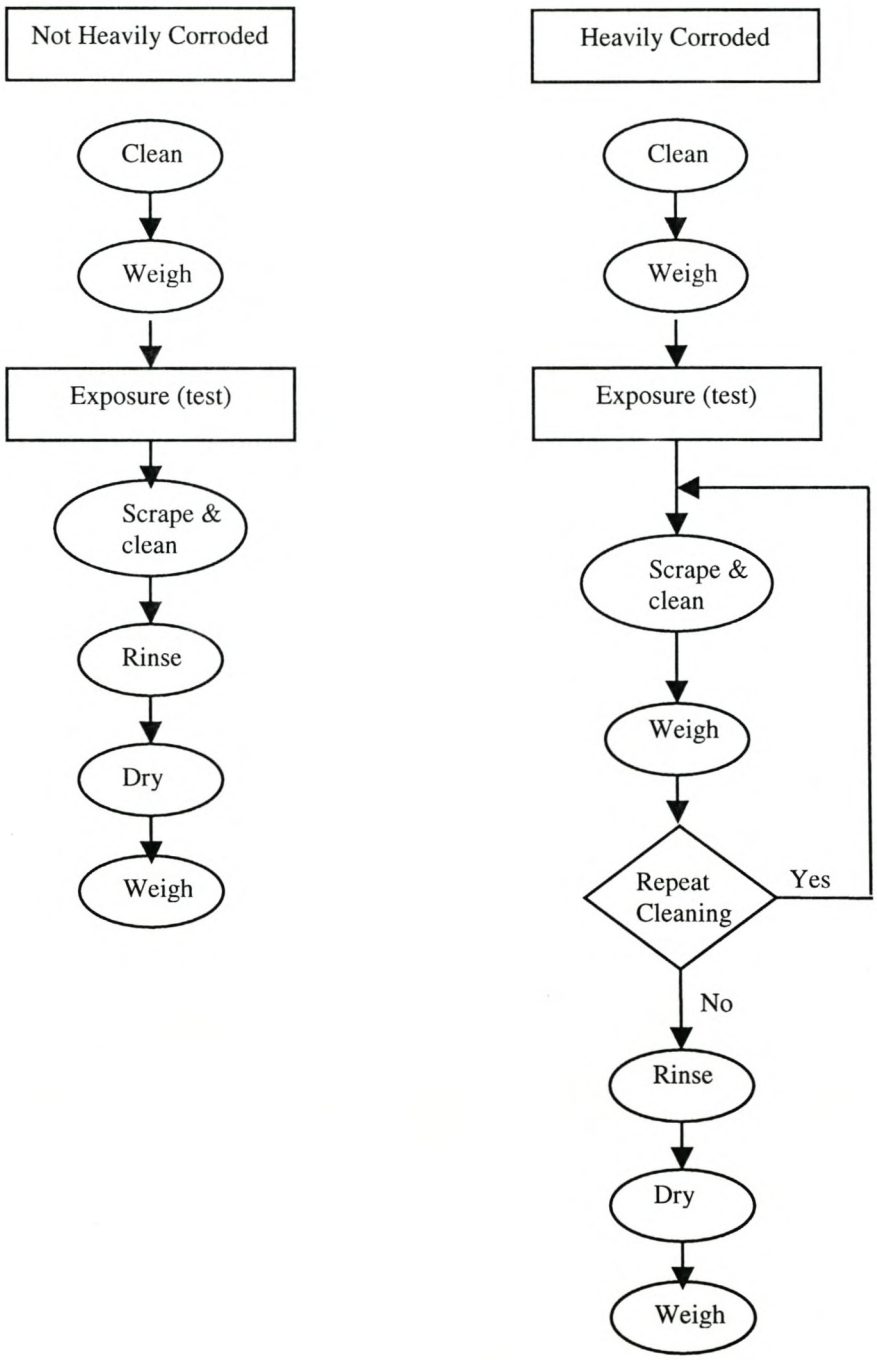
The initial total surface area of the specimen and the mass lost during the test are determined. The average corrosion rate may then be obtained.

The assessment may require further pitting assessment [27].

FLOW CHART

A flow chart illustrating the corrosion cleaning process after testing is given in figure 2.

Fig. 2 Flow Chart: Illustrating Method of Cleaning after Corrosion test



1. **Distance-to-coast :** DDG conductivity and Weather Parameter Results over the first 5 km from the coast

A. Effect of Rainfall

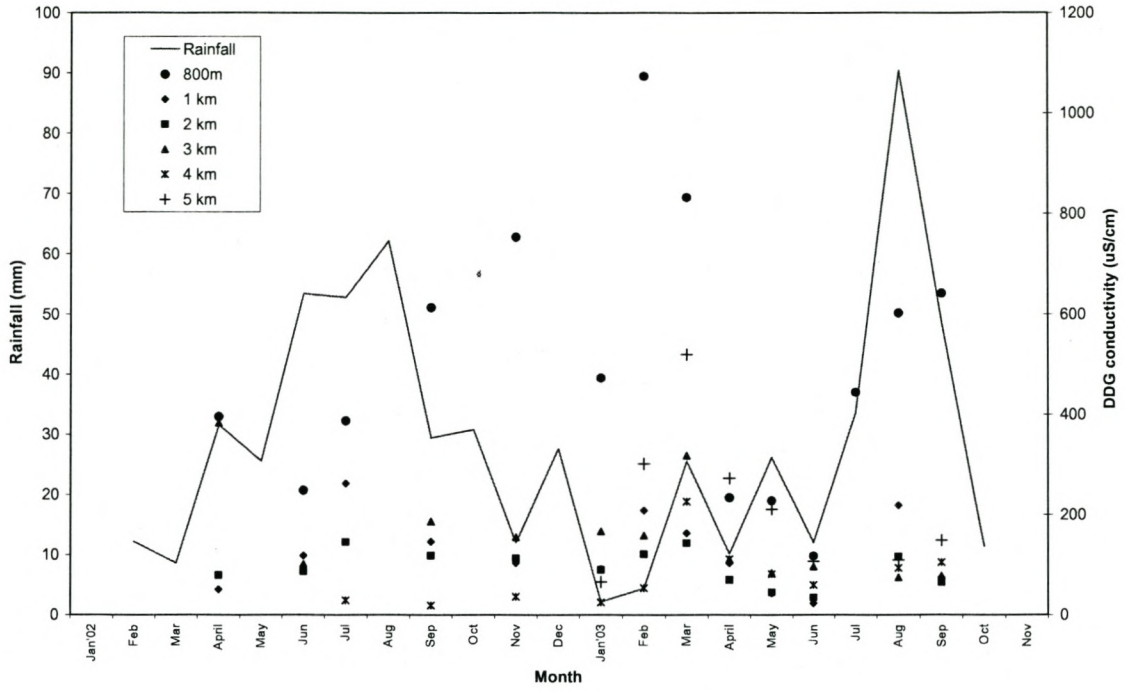


Fig. I.2 Effect of Rainfall on DDG pollution levels up to 5 km from the coast

2. **Height-Above-Ground:** DDG conductivity and Weather Parameter Results as taken on the 120m high mast at Koeberg Meteorological Station

D. Effect of Temperature: Height-above-ground

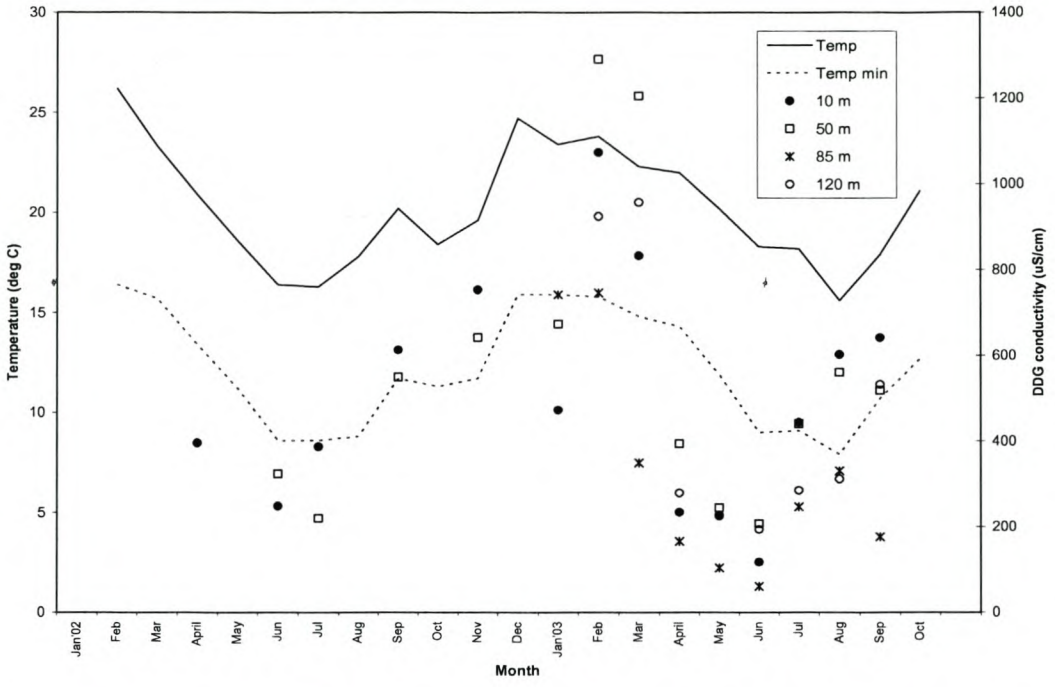


Fig. I.4 Effect of Temperature on DDG pollution levels up to 120 m above ground level

E. Effect of Rainfall: Height-above-ground

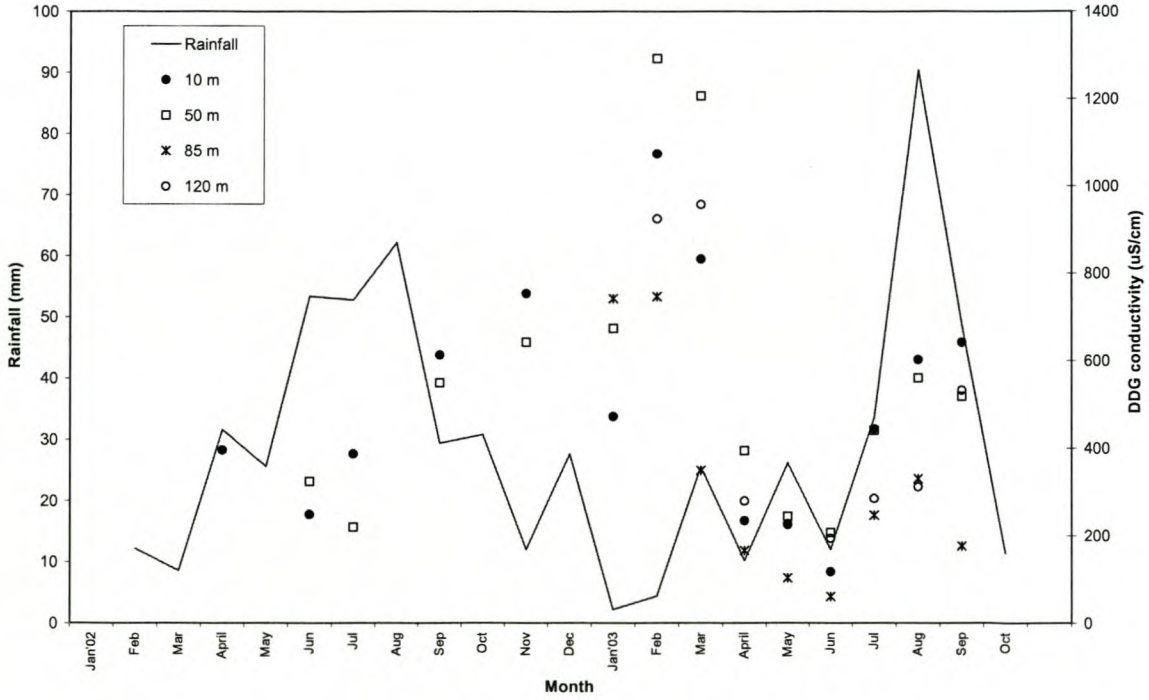


Fig. I.5 Effect of Rainfall on DDG pollution levels up to 120 m above ground level

3. **Height-above-ground: Corrosion test results** and Weather Parameter Results as recorded on the 120m high mast at Koeberg Meteorological Station

G. Effect of Temperature

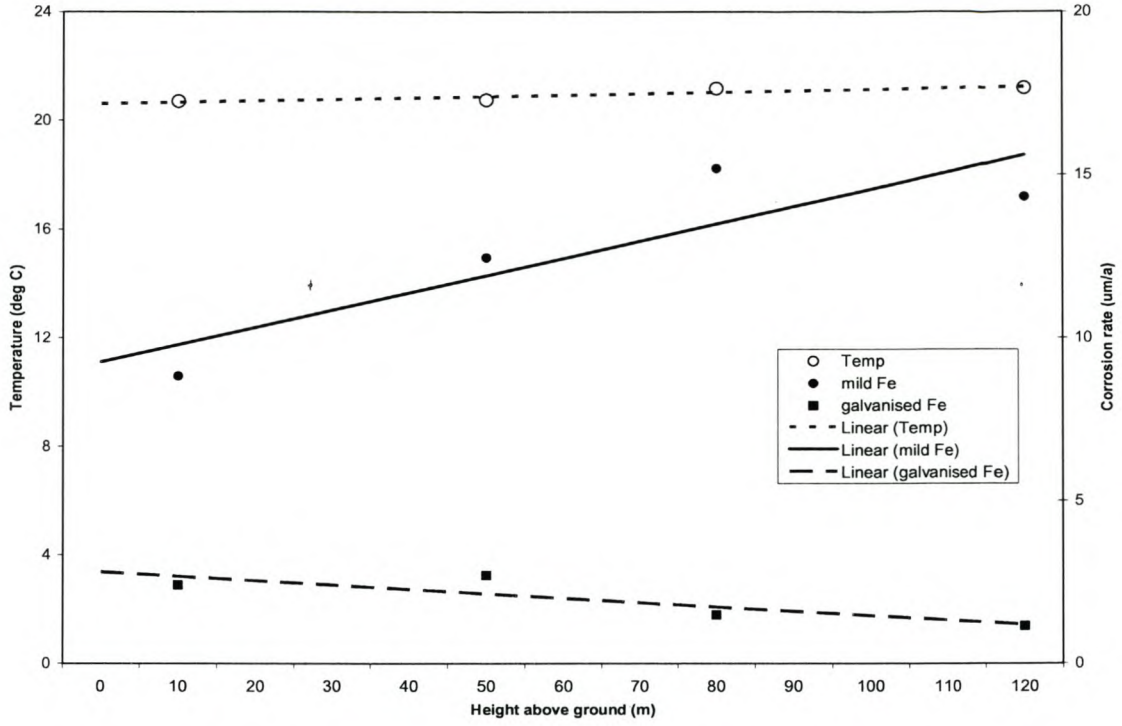


Fig. I.7 Effect of Temperature on metal coupon Corrosion rates up to 120 m above ground level

H. Effect of Wind Speed: summer = South Wester, winter = North Easter

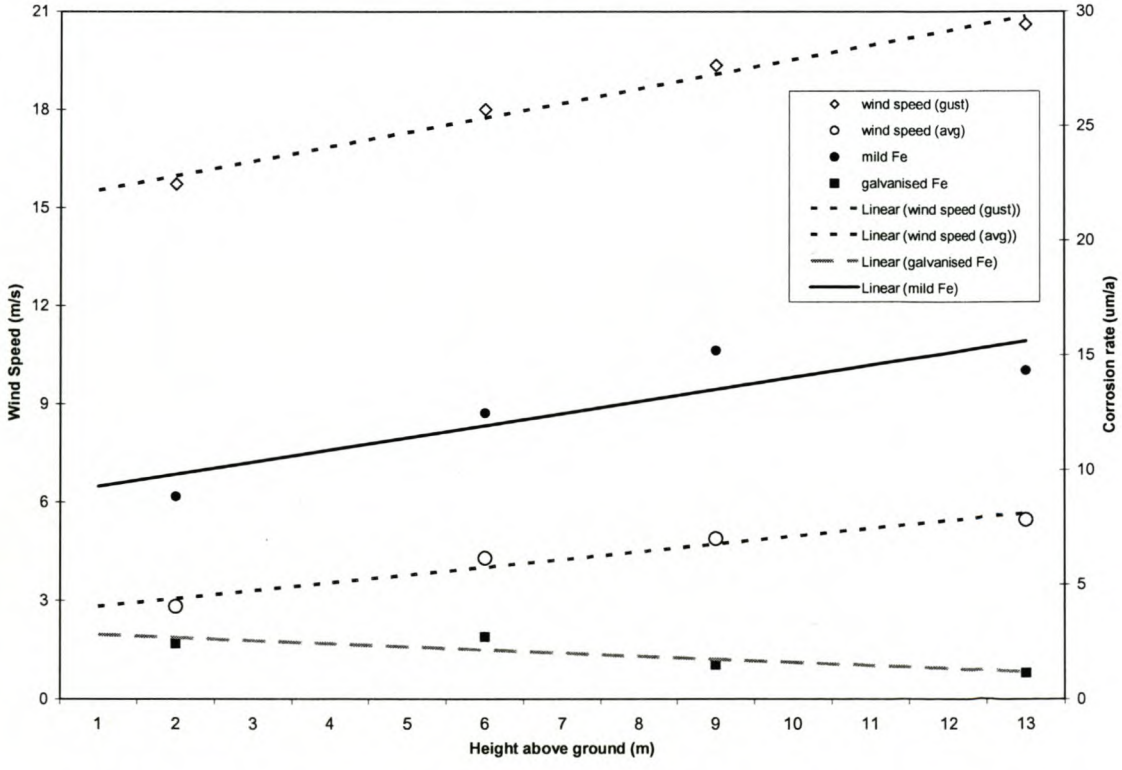


Fig. I.8 Effect of Wind speed on metal coupon Corrosion rates up to 120 m above ground level